



DEPARTMENT OF THE NAVY
NAVAL UNDERSEA WARFARE CENTER
DIVISION NEWPORT
OFFICE OF COUNSEL (PATENTS)
1176 HOWELL STREET
BUILDING 112T, CODE 000C
NEWPORT, RHODE ISLAND 02841-1708

PHONE: 401 832-4736
DSN: 432-4736

FAX: 401 832-1231
DSN: 432-1231



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PATENT COUNSEL
NAVAL UNDERSEA WARFARE CENTER
1176 HOWELL ST.
CODE 000C, BLDG. 112T
NEWPORT, RI 02841

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Inventor Robert M. Payton

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If you have any questions please contact James M. Kasischke, Supervisory Patent Counsel, at 401-832-4230.

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1 Attorney Docket No. 96518

2
3 NATURAL FIBER SPAN REFLECTOMETER PROVIDING A VIRTUAL PHASE
4 SIGNAL SENSING ARRAY CAPABILITY

5
6 Applicant claims the benefit of a provisional application,
7 No. 60/599,435 which was filed on 6 August 2004, and which is
8 entitled "Fiber Span-Based Rayleigh Effect Sensor System with
9 Enhanced Localization Capability" by Robert M. Payton.

10
11 STATEMENT OF GOVERNMENT INTEREST

12 The invention described herein may be manufactured and used
13 by or for the Government of the United States of America for
14 governmental purposes without the payment of any royalties
15 thereon or therefore.

16
17 CROSS-REFERENCE TO RELATED APPLICATIONS

18 "Natural Fiber Span Reflectometer Providing a Spread
19 Spectrum Virtual Sensing Array Capability" (Navy Case No 96650)
20 filed on even date herewith in the name of Robert M. Payton,
21 hereby incorporated herein by reference in its entirety.

22 "Natural Fiber Span Reflectometer Providing A Virtual
23 Signal Sensing Array Capability" (Navy Case No. 96517) filed on

1 even date herewith in the name of Robert M. Payton, hereby
2 incorporated herein by reference in its entirety.

3 "Natural Fiber Span Reflectometer Providing a Virtual
4 Differential Signal Sensing Array Capability" (Navy Case No.
5 96519) filed on even date herewith in the name of Robert M.
6 Payton, hereby incorporated herein by reference in its entirety.

8 BACKGROUND OF THE INVENTION

9 (1) Field of the Invention

10 The present invention relates generally to the field of
11 time-domain reflectometers. More specifically, it relates to
12 such reflectometers which are a part of a photonic system
13 application in which the object of the reflectometry is a span
14 of fiber which has an interrogation signal launch end and a
15 remote end. The invention enables the provision of a linear
16 array of virtual sensors along the span. One particular type of
17 application toward which the invention is directed are acoustic
18 security alarm systems in which the span serves as a perimeter
19 intrusion monitoring line.

20 (2) Description of the Prior Art

21 The U.S. Department of the Navy has been engaged in the
22 development of towed acoustic arrays which are reflectometric
23 systems in which the object of the reflectometry is a fiber span
24 having an interrogation signal launch end and a remote end. One

1 such development involves forming a towed array of acoustic
2 sensors along the span by the costly process of irradiating
3 Bragg reflective gratings into the fiber cable. These
4 reflective gratings form the array of sensors of the
5 reflectometry scheme of these systems. These towed arrays have
6 a length of the order of at least 1.0 km, and the need to
7 irradiate the fiber has resulted in the fiber spans costing
8 hundreds of thousands of dollars each.

9 The Department of the Navy development activities have been
10 further tasked to apply their creative efforts to homeland
11 defense problems. As part of this effort there is under
12 consideration the use of a reflectometer in which a fiber span
13 is the object of the reflectometry. In this scheme, the fiber
14 span provided with acoustic sensors would be used as an
15 intrusion detector to monitor the perimeter of an area desired
16 to be secure. The span lengths for this type of application
17 include lengths of the order of 5km, (links of a U.S. border
18 protection network, oil line protection, chemical plant
19 protection, etc.). In such perimeter monitoring applications
20 thousands of acoustic sensors would be required along the fiber
21 span.

22 The cost of manufacturing such perimeter monitoring spans
23 employing reflective Bragg grating sensors has been an obstacle
24 to their use in perimeter intrusion monitoring applications.

1 Thus, there is considerable interest in the development of a
2 reflectometer system in which a fiber span is the object of the
3 reflectometry optic array that does not require the high cost of
4 Bragg reflective acoustic sensors.

5 Previous effort in solving related problems are described
6 by the following patents:

7 U.S. Patent No. 5,194,847 issued March 16, 1993 to H.
8 Taylor and C. Lee discloses an apparatus for sensing intrusion
9 into a predefined perimeter which comprises means for producing
10 a coherent pulsed light, which is injected into an optical
11 sensing fiber having a first predetermined length and positioned
12 along the predefined perimeter. A backscattered light in
13 response to receiving the coherent light pulses is produced and
14 coupled into an optical receiving fiber. The backscattered
15 light is detected by a photodetector and a signal indicative of
16 the backscattered light is produced. An intrusion is detectable
17 from the produced signal as indicated by a change in the
18 backscattered light. To increase the sensitivity of the
19 apparatus, a reference fiber and interferometer may also be
20 employed.

21 U.S. Patent No. 6,285,806 issued on September 4, 2001 to A.
22 Kersey et al., discloses an apparatus and method for measuring
23 strain in an optical fiber using the spectral shift of Rayleigh
24 scattered light. The interference pattern produced by an air

1 gap reflector and backscatter radiation is measured. Using
2 Fourier Transforms, the spectrum of any section of fiber can be
3 extracted. Cross correlation with an unstrained measurement
4 produces a correlation peak. The location of the correlation
5 peak indicates the strain level in the selected portion of
6 optical fiber.

7 The above patents do not show how to obtain signals
8 representing acoustic pressure signals incident upon a fiber
9 span (to detect perimeter intrusion) at a very large number of
10 sensing stations without involving high manufacturing costs.
11 Consequently, those skilled in the arts will appreciate the
12 present invention which addresses these and other problems.

13

14 SUMMARY OF THE INVENTION

15 The objects of the present invention include the provision
16 of:

17 (1) A time-domain reflectometer wherein an optical fiber span
18 is the object of the reflectometry, and which provides output
19 signals representative of acoustic pressure waves incident the
20 span solely by virtue of the natural, or innate, properties of
21 commercial grade optical fiber cables.

22 (2) The reflectometer described in object number (1), above,
23 capable of providing acoustic wave signal sensing lengths of 5.0
24 km or more.

1 (3) The reflectometer described in object number (2), above,
2 which facilitates the provision of a very large plurality (e.g.
3 5,000 or more) virtual acoustic sensors along the span.

4 (4) The reflectometer described in object number (1), above
5 having a mode of operation which inherently attenuates undesired
6 noises due to span line discontinuities, such as reflections
7 caused by fiber cable couplings.

8 (5) The reflectometer described in objects numbered (1) through
9 (4), above, having special utility as a perimeter intrusion
10 monitoring line for an acoustic security alarm system.

11 (6) The reflectometer described in object numbered (1), above,
12 which is capable of providing output signals in the form of a
13 phase signal which varies linearly with the acoustic pressure
14 wave.

15 (7) The reflectometer described in object numbered (3), above,
16 which is capable of providing output signals in the form of
17 phase differential signals across pairs of the virtual sensors.

18 (8) The reflectometer described in the object number (7),
19 above, providing a capability of programmably selecting a pair,
20 or pairs, of virtual acoustic sensors across which the phase
21 signals are picked off, from among the plurality of virtual
22 signals along the span.

23 These and other objects, features, and advantages of the
24 present invention will become apparent from the drawings, the

1 descriptions given herein, and the appended claims. However, it
2 will be understood that the above listed objects and advantages
3 of the invention are intended only as an aid in understanding
4 aspects of the invention, and not intended to limit the
5 invention in any way, and do not form a comprehensive list of
6 objects, features, and advantages.

7 Accordingly, a time-domain reflectometer is provided for
8 sensing and providing output signals representative of acoustic
9 wave signals incident on the fiber span which is the object of
10 the reflectometry, wherein the innate properties of low cost,
11 commercially available fiber optic cables are employed to create
12 a plurality (upwardly extending to very large numbers, e.g.,
13 5000 and more) virtual sensors.

14 The present invention is implemented as follows:
15 Time and spatial domain multiplexing and de-multiplexing of
16 optical signals is accomplished by an electronic-delay or time
17 of-transversal-delay coupled with modulated-retransmission of a
18 master or reference carrier wave. Each individual optical
19 signal occupies a unique time-delay slot or bin. A master or
20 carrier wave is modulated with each individual optical signal
21 and delayed by the appropriate time interval specific to a
22 particular signal. All such signals are combined and
23 simultaneously transmitted as a composite optical signal to a
24 receiver where these are collected and photodetected. By

1 correlating the photodetected composite optical signal with the
2 master or reference carrier wave, each individual optical signal
3 is sorted or demultiplexed into separate electronic signal
4 channels. The continuous wave nature of the master or reference
5 carrier wave provides more power than a pulsed optical wave and
6 heterodyne optical reception of the invention allows a very low
7 optical detection threshold or noise floor. The invention
8 provides significant improvement over other systems because the
9 optical noise floor is lowered considerably over more
10 conventional means.

11 The invention applies to several applications. The
12 invention allows audio bandwidth (tens of kilohertz bandwidth)
13 providing time-domain reflectometry measurements of fiber
14 optical cables or other optical mediums such as glass, air,
15 water, etc. Other time-domain reflectometry methods do not
16 sample the optical medium fast enough to detect tens of
17 kilohertz bandwidth variations in the medium. The invention
18 also relates to fiber optic sensors and optical sensors
19 generally. A fiber optic sensor array is typically time-domain
20 multiplexed by the time-of-transversal of an interrogation
21 lightwave to each sensor and back to a common optical collection
22 and detection point. The invention relates generally to both
23 amplitude and phase type optical sensor arrays. The invention is
24 an enabling technology for a Department of Navy development

1 known as the Rayleigh Optical Scattering and Encoding (ROSE)
2 sensor system. The spatial separation of segmentation of a ROSE
3 acoustic array into spatial channels is enabled by the
4 invention.

5 The invention relates to acoustic security alarm systems,
6 Naval towed arrays for sensing underwater acoustic signals,
7 fiber optic bugging devices, and many other potential ROSE
8 applications. The invention also relates to non-fiber optical
9 sensors such as: laser velocimeters; lasers imagers; laser
10 radar; laser rangars; and remote laser acoustic, strain, motion
11 or temperature measurement devices.

12

13 BRIEF DESCRIPTION OF THE DRAWINGS

14 A more complete understanding of the invention and many of
15 the attendant advantages thereto will be readily appreciated as
16 the same becomes better understood by reference to the following
17 detailed description when considered in conjunction with the
18 accompanying drawing, wherein like reference numerals refer to
19 like parts and wherein:

20 FIG. 1 is a graphical depiction of certain underlying
21 physical mechanisms of polarization;

22 FIG. 2 is a block diagram helpful in understanding the
23 concept of launch of an interrogation signal along an optical
24 fiber span providing a virtual array of pressure wave sensors by

1 retrieval of backscatter from Rayleigh Optical Scatter (ROS)
2 effects;

3 FIG. 3 is a block diagram of a natural fiber span time-
4 domain reflectometer system in accordance with the present
5 invention;

6 FIG. 4 is an electrical schematic of a balanced heterodyne
7 optic detector circuit;

8 FIG. 5 is an electrical schematic of an alternative
9 embodiment of a photodetector type heterodyner;

10 FIG. 6 is a block diagram of a programmable correlator
11 subsystem, which enables spatial sampling of optical signals on
12 the fiber optic span of the system of FIG. 3, in order to
13 provide a virtual array of acoustic wave sensors therealong;

14 FIG. 7 is a block diagram depiction of a set of phase
15 demodulator circuit assemblies which receives the outputs of the
16 programmable correlator subsystem of FIG. 6;

17 FIG. 8 is a block diagram of one of the phase demodulator
18 circuit assemblies of the set of FIG. 7;

19 FIG. 9 is a block diagram disclosing details of an I & Q
20 demodulator component in a phase demodulator circuit assembly of
21 FIG. 8;

22 FIG. 10 is a block diagram disclosing details of a digital
23 embodiment of the phase detector component phase demodulator
24 circuit assembly of FIG. 8;

1 FIG. 11 is a block diagram disclosing details of an analog
2 embodiment of the phase detector component phase demodulator
3 circuit assembly of FIG. 8;

4 FIG. 12 is a block diagram of a programmable routing and
5 phase signal switching network which provides selective pairing
6 of the outputs of the set of phase demodulators of FIG. 7 to
7 provide differential phase signals across pairs of virtual
8 sensors along the fiber span in accordance with the present
9 invention; and

10 FIG. 13 is a diagrammatic depiction of embodiment of
11 invention of FIG. 3 in which portions of the optical fiber span
12 are wound around a hollow mandrel.

14 DESCRIPTION OF THE PREFERRED EMBODIMENT

15 (1) Description of Underlying Theories

16 a. Heterodyne Optical Detection

17 Optical receivers are built around photodetectors which
18 detect optical power rather than instantaneous electric field.
19 Typically the photodetector output current is proportional to
20 the incident optical power. This relationship severely limits
21 the dynamic range of an incoherent optical receiver because for
22 every decibel of optical power lost in a receiver system two
23 decibels of receiver output current is lost. The square law
24 characteristics of photodetectors limits typical incoherent

optical receivers (often called video detection receivers) to dynamic ranges of less than 80 dB and optical detection noise floors to greater than -80 dBm per Hertz bandwidth. As illustration, suppose an electric field $E_s(t)$ [volt/meter] immersed in a material of impedance η [Ohms] impinges upon a photodetector of responsivity \mathcal{R} [ampere/watt] loaded by resistor R_L and amplified by amplification A , then the optical power P_s by amplification A , is:

$$P_s(t) = \frac{\langle \bar{E}_s(t) \cdot \bar{E}_s(t) \rangle}{\eta} \quad (1)$$

The photodetector output current [amperes] is:

$$i(t) = \mathcal{R}P_s(t) \quad (2)$$

The photoreceiver output [volts] is thus:

$$v(t) = AR_L i(t) = AR_L \mathcal{R}P_s(t) \quad (3)$$

The output fades only if the optical signal power goes to zero because the vector dot product of an optical signal against itself has no polarization or phase effects. This lack of fading due to polarization or phase comes at a cost: phase

1 information is lost and signal to noise ratios are severely
2 impacted.

3 A coherent optical receiver takes advantage of the square
4 law characteristics of photodetectors. A coherent optical
5 receiver combines two optical beams, a signal and a local
6 oscillator, together to form an interference. The interference
7 between these optical waves produces a "beat" which allows the
8 measurement of the phase difference between the signal and the
9 local oscillator. This interference produces an amplitude,
10 polarization, and phase sensitive receiver output.

11 In order to consider these effects a discussion of the
12 polarization state of plane waves is in order. A plane wave
13 contains two orthogonal vector components which are also
14 orthogonal to the direction of propagation of the wave. For
15 purposes of discussion we will consider the plane wave to be
16 oriented so that the vector components of the electromagnetic
17 field lie in an X-Y plane and that the wave propagates in the Z
18 direction. However, this choice of axes is completely
19 arbitrary. In practice, the wave can be oriented in any
20 propagation direction. In order to simplify discussions, a
21 simple change of coordinates will make this discussion
22 completely general.

23 The polarization of an electromagnetic (or optical) plane
24 wave, p , is described by a minimum of five parameters. There

are two basic ways of specifying these parameters. The first way leads to a description which is oriented towards that which is directly obtained from physical measurements.

$$\bar{E}_p(E_{px}, E_{py}, \Phi_{px}, \Phi_{py}, \omega_p, t) = \begin{bmatrix} E_{px}(t) \cos(\omega_p t + \Phi_{px}) \\ E_{py}(t) \cos(\omega_p t + \Phi_{py}) \end{bmatrix} \quad (4)$$

The second manner of describing the polarization state of a wave, p , is oriented more towards the underlying physical mechanisms of polarization. See Figure 1. The description is made in terms of spatial and temporal parameters:

$$\bar{E}_p(E_p, \theta_p, \psi_p, \phi_p, \omega_p, t) = E_p(t) \begin{bmatrix} \cos(\theta_p) & \sin(\theta_p) \\ -\sin(\theta_p) & \cos(\theta_p) \end{bmatrix} \begin{bmatrix} \cos(\psi_p) & 0 \\ 0 & \sin(\psi_p) \end{bmatrix} \begin{bmatrix} \cos(\omega_p t + \phi_p) \\ \sin(\omega_p t + \phi_p) \end{bmatrix} \quad (5)$$

Alternatively, dropping the full variable list in the parentheses and expanding:

$$\bar{E}_p(t) = E_p(t) \begin{bmatrix} \cos(\theta_p) & \sin(\theta_p) \\ -\sin(\theta_p) & \cos(\theta_p) \end{bmatrix} \begin{bmatrix} \cos(\psi_p) & 0 \\ 0 & \sin(\psi_p) \end{bmatrix} \begin{bmatrix} \cos(\phi_p) & -\sin(\phi_p) \\ \sin(\phi_p) & \cos(\phi_p) \end{bmatrix} \begin{bmatrix} \cos(\omega_p t) \\ \sin(\omega_p t) \end{bmatrix} \quad (6)$$

If E_p is constant, the electrical power of this wave can be shown to be constant and equal to:

$$P_p(t) = \frac{\langle \bar{E}_p(t) \cdot \bar{E}_p(t) \rangle}{\eta} = \frac{E_p^2}{2\eta} \quad (7)$$

When two waves, S (signal) and L (local oscillator), interfere at the input of a photoreceiver, the output is:

$$\begin{aligned} v_{out}(t) &= AR_L i(t) = AR_L \Re \frac{\langle \bar{E}_s(t) \cdot \bar{E}_s(t) + \bar{E}_L(t) \cdot \bar{E}_L(t) + 2\bar{E}_L(t) \cdot \bar{E}_s(t) \rangle}{\eta} \\ v_{out}(t) &= v_L(t) + v_s(t) + v_{LS}(t) = AR_L \Re (P_L(t) + P_s(t) + P_{LS}(t)) \end{aligned} \quad (8)$$

If the optical power of the local oscillator and signal lightwaves remain constant, a constant photocurrent develops for the self-interference terms (P_s and P_L). However, if either the local oscillator or the signal lightwaves have any temporal variation in polarization or phase, the cross interference term (P_{LS}) will be time dependent even if the power of each lightwave remains constant. Solving for the cross interference term, we obtain:

$$\begin{aligned} v_{LS}(t) &= \frac{AR_L \Re}{\eta} E_L(t) E_s(t) [\cos(\Delta\theta) \cos(\Delta\psi) \cos(\Delta\omega t + \Delta\phi) + \sin(\Delta\theta) \sin(2\bar{\psi}) \sin(\Delta\omega t + \Delta\phi)] \\ v_{LS}(t) &= 2AR_L \Re \sqrt{P_L(t) P_s(t)} [\cos(\Delta\theta) \cos(\Delta\psi) \cos(\Delta\omega t + \Delta\phi) + \sin(\Delta\theta) \sin(2\bar{\psi}) \sin(\Delta\omega t + \Delta\phi)] \end{aligned} \quad (9)$$

Where the following definitions are made:

$$\begin{aligned}
\Delta\theta &= \theta_s - \theta_L \\
\Delta\psi &= \psi_s - \psi_L \\
2\bar{\psi} &= \psi_s + \psi_L \\
\Delta\omega &= \omega_s - \omega_L \\
\Delta\phi &= \phi_s - \phi_L
\end{aligned} \tag{10}$$

The optical cross-interference portion of the receiver output will fade due to polarization even if the local oscillator and the signal lightwaves both do not have zero optical powers. This condition will occur if:

$$O = \cos(\Delta\theta)\cos(\Delta\psi)\cos(\Delta\omega t + \Delta\phi) = \sin(\Delta\theta)\sin(2\bar{\psi})\sin(\Delta\omega t + \Delta\Phi) \tag{11}$$

Also, equivalently when the condition will occur:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos(\Delta\theta)\cos(\Delta\psi)\cos(\Delta\omega t + \Delta\phi) \\ \sin(\Delta\theta)\sin(2\bar{\psi})\sin(\Delta\omega t + \Delta\phi) \end{bmatrix} \tag{12}$$

When heterodyne optical detection is employed ($\Delta\omega$ is non-zero, the local oscillator has a different frequency from the signal), the conditions for a fade are shown in Table 1. When homodyne detection is employed ($\Delta\omega$ is zero), both phase and polarization fading occur. The conditions for a homodyne fade are shown in Table 2. Heterodyne detection is therefore seen to

be superior to homodyne because the probability of a fade is fully one half as likely.

Table 1: Heterodyne Fading Conditions

Type of Fade (k is an integer)	Required Simultaneous Conditions for a Fade to Occur	
Orthogonal Rotation and Opposite Ellipticity	$\Delta\theta = (2k+1)\pi/2$	$\psi_s + \psi_L = 0$
Orthogonal Rotation and Equal Circular Ellipticity	$\Delta\theta = (2k+1)\pi/2$	$\psi_s + \psi_L \pm \pi$
Equal Rotation and Orthogonal Ellipticity	$\Delta\theta = 0$	$\Delta\psi = \pm\pi/2$
Opposite Rotation and Orthogonal Ellipticity	$\Delta\theta = \pm\pi$	$\Delta\psi = \pm\pi/2$

Table 2: Homodyne Fading Conditions

Type of Fade (k and m are integers)	Required Simultaneous Conditions for a Fade to Occur	
Orthogonal Rotation and Opposite Ellipticity	$\Delta\theta = (2k+1)\pi/2$	$\psi_s + \psi_L = 0$
Orthogonal Rotation and Equal Circular Ellipticity	$\Delta\theta = (2k+1)\pi/2$	$\psi_s + \psi_L \pm \pi$
Equal or Opposite Rotation and Orthogonal Ellipticity	$\Delta\theta = k\pi$	$\Delta\psi = \pm\pi/2$
Orthogonal Rotational and Equal or Opposite Phase	$\Delta\theta = (2k+1)\pi/2$	$\Delta\phi = m\pi$

Given the conditions for and the functional relation of a fade, the question now arises as to how a fade can be prevented. Since the signal is being measured, no a priori knowledge is assumed and therefore E_s , θ_s , ψ_s , ϕ_s are all probably unknown quantities. If fading is prevented, then no loss of information occurs and determination of these four parameters is possible.

1 In order to decode the optical receiver output into these
 2 parameters, at least four independent measurements must be made
 3 to uniquely determine these four independent variables.
 4 However, if the interfering optical beam (or beams) of the local
 5 oscillator are unknown, then additional independent measurements
 6 must be made (four additional measurements for each unknown
 7 beam) to determine the E_L , θ_L , Ψ_L , or Φ_L for each optical beam of
 8 the local oscillator. The cross-reference output of the
 9 photoreceiver, $v_{LS}(t)$, offers the only means by which to measure
 10 these parameters. If the parameters cannot be determined from
 11 this output, then an optical fade cannot be ruled out.

12 We shall now examine the information which can be gleaned
 13 from this output. Define the following functions.

14

15

$$\begin{aligned}
 16 \quad v_i(E_L, E_s, \Delta\theta, \Delta\psi) &= \frac{AR_L \Re}{2\eta} E_L(t) E_s(t) \cos(\Delta\theta) \cos(\Delta\psi) = AR_L \Re \sqrt{P_L(t) P_s(t)} \cos(\Delta\theta) \cos(\Delta\psi) \\
 v_q(E_L, E_s, \Delta\theta, 2\bar{\psi}) &= \frac{AR_L \Re}{2\eta} E_L(t) E_s(t) \sin(\Delta\theta) \sin(2\bar{\psi}) = AR_L \Re \sqrt{P_L(t) P_s(t)} \sin(\Delta\theta) \sin(2\bar{\psi})
 \end{aligned}
 \tag{13}$$

17

18 In the homodyne case ($\Delta\omega$ is zero), we obtain the following
 19 output:

20

$$\begin{aligned}
 21 \quad v_{LS}(t) &= 2AR_L \Re \sqrt{P_L(t) P_s(t)} (\cos(\Delta\theta) \cos(\Delta\psi) \cos(\Delta\phi) + \sin(\Delta\theta) \sin(2\bar{\psi}) \sin(\Delta\phi)) \\
 v_{LS}(t) &= 2v_i(E_L, E_s, \Delta\theta, \Delta\psi) \cos(\Delta\phi) + 2v_q(E_L, E_s, \Delta\theta, 2\bar{\psi}) \sin(\Delta\phi)
 \end{aligned}
 \tag{14}$$

The homodyne output only allows the measurement of one quantity. The output provides only one independent measurement (one equation) whereas a minimum of four are required. In the heterodyne case ($\Delta\omega$ is non-zero), the output is:

$$\begin{aligned} v_{LS}(t) &= 2AR_L \Re \sqrt{P_L(t)P_s(t)} (\cos(\Delta\theta)\cos(\Delta\psi)\cos(\Delta\omega t + \Delta\phi) + \sin(\Delta\theta)\sin(2\bar{\psi})\sin(\Delta\omega t + \Delta\phi)) \\ v_{LS}(t) &= \frac{AR_L \Re}{\eta} E_L(t)E_s(t) (\cos(\Delta\theta)\cos(\Delta\psi)\cos(\Delta\omega t + \Delta\phi) + \sin(\Delta\theta)\sin(2\bar{\psi})\sin(\Delta\omega t + \Delta\phi)) \quad (15) \\ v_{LS}(t) &= 2v_i(E_L, E_s, \Delta\theta, \Delta\psi)\cos(\Delta\omega t + \Delta\phi) + 2v_o(E_L, E_s, \Delta\theta, 2\bar{\psi})\sin(\Delta\omega t + \Delta\phi) \end{aligned}$$

Since sine and cosine waves are orthogonal, the heterodyne receiver provides two independent measurements by mixing down to baseband the $\Delta\omega$ radian frequency components. Thus, two outputs are obtained:

$$\begin{aligned} V_i(t) &= \langle v_{LS}(t) \cos(\Delta\omega t) \rangle = v_i(E_L(t), E_s(t), \Delta\theta(t), \Delta\psi(t)) \cos(\Delta\phi(t)) \\ V_o(t) &= \langle v_{LS}(t) \sin(\Delta\omega t) \rangle = v_o(E_L(t), E_s(t), \Delta\theta(t), 2\bar{\psi}(t)) \sin(\Delta\phi(t)) \end{aligned} \quad (16)$$

b. Correlation or Time-Delay Multiplexing

In many optical sensor applications, the lightwave signal heterodyne-detected by the photodetector system is a composite optical signal formed from the superposition of many individual optical signals. When the receiver lightwave is generated by backscatter, the composite optical signal is the superposition

1 of individual light signals generated by a continuum of
2 reflections of an interrogation light source. The temporal and
3 spatial characteristics of each reflector or reflective region
4 creates a modulation of the interrogation light source. The
5 time-delay, amplitude, polarization and phase states control the
6 backscattered-modulation of these individual optical signals
7 arriving at the photodetector with a unique time-delay interval
8 can be separated into channels which sort the optical signals
9 into time-delay slots or bins. Depending upon how the signals
10 are generated, these channels can represent spatial regions in
11 space or time-delay slots of a time-domain reflectometer
12 mechanism.

13 Let an interrogation lightwave source be generated by
14 modulating the amplitude, phase or polarization of a coherent
15 lightwave with a time-structured correlation code, $c(t)$. The
16 correlation code, $c(t)$ can be a series of pulses, chirps, binary
17 sequences or any other type of code which provides the required
18 correlation characteristics. If the lightwave source is:

19

$$20 \quad E_{ss}(t) = E_{ss} \cos(\omega_s t) \quad (17)$$

21

22 Then an amplitude modulated interrogation source is:

23

$$24 \quad E_i(t) = \mu_A c(t) E_{ss} \cos(\omega_s t) \quad (18)$$

1 Alternatively, a phase modulated interrogation source is:

$$E_i(t) = E_{ss} \cos(\omega_s t + \mu_p c(t)). \quad (19)$$

5 If $c(t)$ is chosen to be temporally structured properly, then:

$$R_i(\tau) = \langle E_i(t) E_i(t + \tau) \rangle \approx \begin{cases} \frac{E_{ss}^2}{2}; \tau \approx 0 \\ 0; \text{otherwise} \end{cases} \quad (20)$$

9 $c(t)$ must be chosen so that an a priori decoding/demultiplexing
10 function, $d(t)$, exists such that:

$$b(t, \tau) = \langle d(t) E_i(t + \tau) \rangle \approx \begin{cases} \xi E_{ss} \cos(\Delta\omega t + \phi); \tau \approx 0 \\ 0; \text{otherwise} \end{cases} \quad (21)$$

14 For instance, suppose the interrogation wave is:

$$E_i(t) = \mu_A c(t) E_{ss} \cos(\omega_s t) \quad (22)$$

18 and:

$$R_c(\tau) = \langle c(t) c(t - \tau) \rangle \approx \begin{cases} 1; \tau \approx 0 \\ 0; \tau \neq 0 \end{cases} \quad (23)$$

then a valid decoding and temporal and spatial domains
demultiplexing function is:

$$d(t) = \mu_d C(t) E_L \cos((\Delta\omega + \omega_s)t + \phi)$$

$$b(t, \tau) = \langle d(t - \tau) E_i(t) \rangle = \begin{cases} \frac{\mu_d \mu_A E_{ss} E_L}{2} \cos(\Delta\omega(t - \tau) + \phi - \omega_s \tau); \tau \approx 0 \\ 0; \text{otherwise} \end{cases} \quad (24)$$

Therefore, delaying the correlation decoding/demultiplexing
function $d(t)$ allows demultiplexing of delay multiplexed signals
identifiable by speed of propagation and distance of flyback
travel. Suppose an optical wave is formed a summation of
delayed signals modulated onto the interrogation wave $E_i(t)$, then
the received wave, $E_b(t)$, is:

$$E_b(t) = \sum_{n=1}^N A_n(t - \tau_n) \mu_A c(t - \tau_n) E_{ss} \cos(\omega_s(t - \tau_n) + \Phi_n(t - \tau_n)) \quad (25)$$

Then multiplying by the decoding/demultiplexing function,
 $d(t - \tau_m)$, we obtain:

$$d(t) = \mu_d c(t) E_L \cos((\Delta\omega + \omega_s)t + \phi)$$

$$b(t, \tau_m) = \langle d(t - \tau_m) E_b(t) \rangle \quad (26)$$

$$b(t, \tau_m) \approx \frac{\mu_d \mu_A E_{ss} E_L}{2} A_m(t - \tau_m) \cos(\Delta\omega(t - \tau_m) + \phi - \omega_s \tau_m + \Phi_m(t - \tau_m)).$$

1 Because τ_n is unique, the amplitude signal $A_m(t-\tau_m)$ and the phase
2 signal $\Phi_m(t-\tau_m)$ are both extracted from $E_b(t)$ by multiplying by
3 the decoding/demultiplexing function, $d(t-\tau_m)$. The technique is
4 applicable to a wide variety of other optical signal
5 multiplexing applications. Specifically, the technique can be
6 used to spatially separate optical signals arriving from a
7 temporally varying time-domain reflectometer optical backscatter
8 process from an array of fiber optic acoustic sensors.

9 (2) Description and Operation of the Rayleigh Optical
10 Scattering and Encoding (ROSE) System

11 a. ROSE Optical Phase Sensor Interrogation Enables Sensor
12 Subsystem

13 In order to more fully describe the capabilities and new
14 features of the invention, the application of the invention to a
15 subsystem 1, FIG. 2, of ROSE which launches an interrogation
16 signal onto fiber span 9 and retrieves lightwave back
17 propagation from a continuum of locations along the span. Back
18 propagation mechanisms may include Rayleigh Optical Scattering
19 (ROS) and other effects generated within the optical fiber.
20 Rayleigh Optical Scattering (ROS) in an optical fiber
21 backscatters light incident upon the fiber. The incident light
22 transverses down the optical fiber to the scattering
23 point/region. At the scattering region the incident light is

1 backscattered back up the optical fiber. As the light
2 transverses the round trip optical path (i.e., distance of
3 flyback travel) any disturbance of the fiber which increase or
4 decrease the optical path length will cause the phase of the
5 incident and backscattered light to be modulated. Suppose a
6 pressure is applied to the optical fiber. The pressure
7 elongates the path length of the light transversing the region.

8 Refer to FIG. 2. for the following discussion. In the
9 FIGS. like parts correspond to like numbers. Let $p(t,z)$ be
10 pressure applied to the outside of the optical fiber at time, t ,
11 and at point or length, z , along the fiber axis. Then if an
12 interrogation optical wave, $E_i(t)$, generated by laser 3, passed
13 through optical coupler 4 and modulated by optical modulator 5
14 is applied to optical coupler 7, this results in the following
15 output interrogation wave, $E_i(t)$, being transmitted down the
16 fiber 9:

$$E_i(t) = \mu_A c(t) E_{ss} \cos(\omega_s t). \quad (27)$$

17
18
19
20 The backscattered wave, $E_b(t)$, arriving back at an optical
21 coupler 7 from ROSE fiber optic array 9 passes into optical path
22 11. The backscattered light which arrives at optical path 11 is
23 the summation of all light backscattered from a continuum of
24 locations along the length of the ROSE fiber optic span 9. As

will later herein be described in detail, fiber 9 has a longitudinal strain component enhancing coating 12. If $r(z)$ is the reflection density at point or length z along the fiber and c_L is the optical wave speed, then the backscattered light after a pressure $p(t,z)$ is applied to fiber is represented mathematically as:

$$E_b(t) = \int_0^{\infty} r(\hat{z}(t, z)) \mu_A c \left(t - \frac{2\hat{z}(t, z)}{c_L} \right) E_{ss} \cos \left(\omega_s \left(t - \frac{2\hat{z}(t, z)}{c_L} \right) \right) dz \quad (28)$$

where:

$$\hat{z}(t, z) = z + \mu_L \int_0^z p(t, x) dx. \quad (29)$$

If the distributed reflection, $r(z)$ is essentially independent of the applied pressure, $p(t,z)$ then the backscatter is:

$$E_b(t) = \int_0^{\infty} r(z) \mu_A c \left(t - \frac{2\hat{z}(t, z)}{c_L} \right) E_{ss} \cos \left(\omega_s \left(t - \frac{2\hat{z}(t, z)}{c_L} \right) \right) dz. \quad (30)$$

Since optical path length change caused by the applied pressure, $p(t,z)$ is usually extremely small (on the order of 10^{-6}

1 to 10^1 times an optical wavelength), the backscattered light from
2 each z distance down the fiber arrives at the optical path 11
3 with a transversal delay, $\tau(t,z)$, equal to:

4

$$5 \quad \tau(t,z) \approx \frac{2z}{c_L}. \quad (31)$$

6

7 Therefore, to receive the signal S_1 backscattered from the
8 fiber region at length-down-the-fiber $z=L_1$, the correlational
9 multiplexing characteristic of the transmitted interrogation
10 light can be utilized. Multiplication of the total
11 backscattered optical signal by the correlation
12 decoding/demultiplexing function, $d(t-\tau(t,z_1))$, produces an output
13 which contains the signal, S_1 , backscattered from a distance L_1
14 down the fiber and rejects signals originating from other fiber
15 regions, such as S_2 , S_n and etc. Representing this process
16 mathematically, the resulting channel output, $B(t, L_1)$ is
17 obtained as follows:

$$\begin{aligned}
b(t, \tau_1) &= \langle d(t - \tau_1) E_b(t) \rangle = \left\langle d\left(t - \frac{2L_1}{c_L}\right) E_b(t) \right\rangle = B(t, L_1) \\
d\left(t - \frac{2L_1}{c_L}\right) &= \mu_d c \left(t - \frac{2L_1}{c_L}\right) E_L \cos\left((\Delta\omega + \omega_s)\left(t - \frac{2L_1}{c_L}\right) + \phi\right) \\
E_b(t) &= \int_0^{\infty} r(z) \mu_A c \left(t - \frac{2z}{c_L}\right) E_{ss} \cos\left(\omega_s\left(t - \frac{2\hat{z}(t, z)}{c_L}\right)\right) dz \\
\Phi(z, L_1) &= \phi - \frac{2(\Delta\omega + \omega_s)L_1}{c_L} + \Delta\omega \frac{2z}{c_L}
\end{aligned} \tag{32}$$

$$\begin{aligned}
B(t, L_1) &= \mu_d \mu_A E_L E_{ss} \int_0^{\infty} r(z) R_c\left(\frac{2(z - L_1)}{c_L}\right) \cos\left(\Delta\omega t + \Phi(z, L_1) + \frac{2\mu_L \omega_S}{c_L} \int_0^z p(t, x) dx\right) dz \\
\Delta\Phi(t, z) &= \Phi(z, L_1) + \frac{2\mu_L \omega_S}{c_L} \cdot \int_0^z p(t, x) dx \\
B(t, L_1) &= V_E \int_0^{\infty} r(z) R_c\left(\frac{2(z - L_1)}{c_L}\right) \cos(\Delta\omega t + \Delta\Phi(t, z)) dz \\
B(t, L_1) &\approx V_E r_{L_1} \cos\left(\Delta\omega t + \Phi_{L_1} + \frac{2\mu_L \omega_S}{c_L} \cdot \int_0^{L_1} p(t, x) dx\right)
\end{aligned} \tag{33}$$

3

4 Because of the correlation properties of the interrogation

5 light, the autocorrelation function $R_c(\tau)$ is very small at all

6 spatial locations except those in the vicinity of $z=L_1$.

7 Therefore, all signals originating anywhere else are rejected.

8 Furthermore, the phase of the channel output at location L_1 will

9 be the summation or integration of all pressure changes along

10 the bi-directional transversal path. This unusual phenomenon

11 has been demonstrated with experimental hardware.

1 Once the correlation process isolates the optical signal
 2 originating from a spatial region, the signal must be phase
 3 demodulated to extract the pressure information. The signal is
 4 I (in phase) and Q (quadrature phase) demodulated is:

$$\begin{aligned}
 B_I(t, L_1) &= \langle B(t, L_1) \cos(\Delta\omega t) \rangle \\
 B_I(t, L_1) &\approx V_E r_{L_1} \cos \left(\Phi_{L_1} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_1} p(t, x) dx \right) = V_1 \cos(\Phi_1) \\
 B_Q(t, L_1) &= \langle B(t, L_1) \sin(\Delta\omega t) \rangle \\
 B_Q(t, L_1) &\approx -V_E r_{L_1} \sin \left(\Phi_{L_1} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_1} p(t, x) dx \right) = -V_1 \sin(\Phi_1).
 \end{aligned} \tag{34}$$

6
 7 Then I & Q, or cosine phase and sine phase outputs are
 8 converted into either phase rate or phase outputs with simple
 9 analog or digital hardware. The phase, so demodulated, allows
 10 the inference of information about the acoustic pressure down
 11 the fiber to the measurement point.

12 Once the I & Q outputs are generated, the temporal phase
 13 state of $B(t, L_1)$ can be determined by one of several types of
 14 phase demodulation processes. The phase state of the region of
 15 L_1 spatial delay is therefore:

$$\Phi_1 = \Phi_{L_1} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_1} P(t, x) dx. \tag{35}$$

Likewise, the plurality (which may be a large number, e.g., 5000) of optical signals arising with spatial delays, such as the propagation time for flyback travel to L_2 or L_n , can be correlated out of the backscattered signal $E_b(t)$. These are:

$$\begin{aligned} B(t, L_2) &\approx V_E r_{L_2} \cos \left(\Delta\omega t + \Phi_{L_2} + \frac{2\mu_L \omega_s}{C_L} \cdot \int_0^{L_2} p(t, x) dx \right) \\ B(t, L_n) &\approx V_E r_{L_n} \cos \left(\Delta\omega t + \Phi_{L_n} + \frac{2\mu_L \omega_s}{C_L} \cdot \int_0^{L_n} p(t, x) dx \right) \end{aligned} \quad (36)$$

With corresponding phase signals of:

$$\begin{aligned} \Phi_2 &= \Phi_{L_2} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_2} p(t, x) dx \\ \Phi_n &= \Phi_{L_n} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_n} p(t, x) dx. \end{aligned} \quad (37)$$

The phase signals, obtained by phase demodulation of each $B(t, L_m)$, represent a pressure field $p(t, z)$ which is integrated along the length, z , of the fiber. Therefore, rather than directly measure $p(t, z)$ the sensor provides all of the accumulated pressure effects down the fiber to the measurement point, L_m (where m is integer corresponding to the measurement point). In sensor arrays, it is usually desired to detect the pressure over a specific measurement region. If two optical

1 signals S_j and S_k are received from measurement lengths L_j and L_k ,
 2 the corresponding demodulated phases Φ_j and Φ_k are:

$$\begin{aligned}\Phi_j &= \Phi_{L_j} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_j} p(t, x) dx \\ \Phi_k &= \Phi_{L_k} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_k} p(t, x) dx.\end{aligned}\tag{38}$$

4
 5 A sensor between the lengths down the fiber of L_j and L_k
 6 ($L_k > L_j$) is formed by subtracting the two phases:

$$\begin{aligned}\Phi_k - \Phi_j &= \Delta\Phi_{kj} = \left(\Phi_{L_k} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_k} p(t, x) dx \right) - \left(\Phi_{L_j} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_0^{L_j} p(t, x) dx \right) \\ \Delta\Phi_{kj} &= \Phi_{L_k} - \Phi_{L_j} + \frac{2\mu_L \omega_s}{c_L} \cdot \left(\int_0^{L_k} p(t, x) dx - \int_0^{L_j} p(t, x) dx \right) \\ \Delta\Phi_{kj} &= \Phi_{L_k} - \Phi_{L_j} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_{L_j}^{L_k} p(t, x) dx \\ \Delta\Phi_{kj} &= \Delta\Phi_{L_k L_j} + \frac{2\mu_L \omega_s}{c_L} \cdot \int_{L_j}^{L_k} p(t, x) dx.\end{aligned}\tag{39}$$

8 The resulting sensor is of length $\Delta L = L_k - L_j$ with a center
 9 position of $(L_k + L_j)/2$. The differencing of phase signals Φ_j and
 10 Φ_k into a new phase signal $\Delta\Phi_{kj}$, allows a virtual sensor of
 11 arbitrary position and length to be formed. The resulting
 12 spatially differential sensor also adds the advantage of
 13 minimizing other effects such as lead-in fiber strain or
 14 vibration which create unwanted phase signals.

1 The above phenomena illustrates that when the interrogation
2 light is properly encoded, a ROSE (Rayleigh Optical Scattering
3 and Encoding) sensor system is enabled. The subject invention
4 therefore enables the ROSE concept. The subject invention
5 enables spatial discrimination of the optical backscatter
6 effects in a ROSE sensor. The spatial differencing technique
7 rejects unwanted common mode signals inadvertently introduced in
8 fiber leads down to the sensor region. The invention also
9 applies in a similar manner to more conventional fiber optic
10 acoustic sensor arrays (i.e., those having Bragg reflective
11 grating sensors) or to non-fiber optic remote optical sensors
12 which detect phase.

13 b. Pointwise Signal Delay Multiplexing

14 The invention also applies to point-wise non-distributed
15 sensors or artificially generated multiplexing by electronics
16 means. The interrogation lightwave can be intercepted and
17 retransmitted back to the receiver with an artificial,
18 electronically generated delay, as a means of delay/correlation
19 multiplexing many channels.

20 (3) Description of a Fiber System Implementation

21 The invention can be realized with bulk optical, fiber
22 optical or integrated optical components. For simplicity, a
23 fiber optic implementation will be presented. However, the
24 fiber optic embodiment is being presented without intent of

1 limitation. The teachings of the invention can be used to
2 implement a reflectometer system in accordance with the present
3 invention using these and other instrumentalities providing a
4 light path that has the innate property of producing back
5 propagation of portions of an interrogation signal at a
6 continuum of locations along the length of the propagation path
7 therethrough.

8 a. Optical Transmitter and Time-delay Multiplexing
9 Process.

10 FIG. 3 is an illustrative block diagram implementation of the
11 Rayleigh optical scattering and encoding (ROSE) sensor system 2.
12 Like parts correspond to like numbers. A lightwave from
13 transmitter laser, 3, is propagated through optical coupler or
14 beamsplitter, 4. The smaller portion of the transmitter laser
15 power split off by optical coupler, 4, is passed by optical
16 path, 39, to the phase locking means optical receiver 35. The
17 larger portion of the transmitter laser light power is split by
18 optical coupler, 4, and propagated to optical modulator, 5. The
19 optical modulator, 5, modulates the laser light passing from
20 optical coupler, 4, with correlation code, $c(t)$, as
21 electronically generated in master correlation code generator,
22 53, and amplified by amplifier, 49. The correlation code, $c(t)$,
23 is modulated onto the laser light in optical modulator, 5. This
24 modulated light comprises the optical interrogation lightwave,

1 $E_i(t)$. The optical modulator, 5, may modulate the amplitude,
2 polarization or phase of the laser light subject to the
3 teachings of the invention. The interrogation lightwave is
4 propagated from optical modulator, 5, to optical coupler,
5 beamsplitter or circulator, 7. The interrogation lightwave
6 passes through the optical coupler, 7, into optical fiber or
7 other light propagation medium, 9. Hereinafter, "down",
8 indicates a transversal on the optical path, 9, away from
9 coupler, 7; "up" indicates a transversal on the optical path 9
10 toward the optical coupler, beamsplitter or circulator, 7. The
11 interrogation lightwave which transverses down the optical fiber
12 or medium 9 is modulated and is backscattered or returned by
13 other means with equivalent optical path lengths (equivalent to
14 a time delay), $L_1, L_2...L_n$ corresponding to sensors or multiplexed
15 channels $S_1, S_2...S_n$. The returned interrogation lightwave is a
16 composite optical signal modulated by signals due to the S_1
17 through S_n modulating and time-domain multiplexing actions.

18 More particularly, the propagation of the optical spread-
19 spectrum interrogation signal down the continuous full span of
20 the optical fiber span, signal launch end to remote end, causes
21 a back-propagating composite optical signal, which is the linear
22 summation, or integration spatially, of all of the individual,
23 continuous, or continuum of back-reflections along the span of
24 the optical fiber.

1 One component of this composite signal is comprised of the
2 naturally occurring continuum of optical back reflections
3 (including Rayleigh optical scattering ((ROS)) effects) of the
4 optical spread spectrum carrier signal that is formed by
5 modulating the primary carrier signal by the spectrum spreading
6 signals. Another component is comprised of the artificially
7 occurring optical back reflections, either-point wise
8 reflections or distributed reflections, of the optical spread
9 spectrum carrier signal that is formed due to propagation
10 discontinuities as the result of presence of a fiber cable
11 coupler in span 9. Still another component comprised of the
12 continuum of modulations at locations along the span of the
13 reflected signals due to longitudinal components of optical path
14 length change, causing a delay in the reflected signal,
15 experienced by the fiber optical span along its length.

16 Such optical path length change or delay may be caused by a
17 variety of possible sources including acoustic pressure waves
18 incident to the fiber, electromagnetic fields coupled to the
19 fiber, mechanical strain or pressure on the fiber, thermal
20 strain or pressure induced in the fiber, or other means of
21 causing change in the optical path length. Use of the acoustic
22 pressure waves mode of changing path length in perimeter
23 intrusion monitoring systems is the principle embodiment
24 illustrated herein. In this use, optical fiber span 9 is

1 employed to provide an array of virtual geophones buried at a
2 range of depths beneath the surface of the ground of about
3 between six (6) inches and one (1) foot, to sense motion of an
4 object on the surface of the ground. The acoustic pressure wave
5 sensing mode is also useful to sense seismic signals, as for
6 example as linear arrays inserted into casing structures of an
7 existing oil wells. Predetermined artificial pressure wave
8 producing shocks are imparted into the ground, and the responses
9 from the sensor are used to locate secondary oil deposits. The
10 acoustic pressure wave sensing mode is further useful for
11 employing span 9 as an array of virtual hydrophones, with the
12 media which couples the signals to the hydrophones at least in
13 part being the body of water in which the array is immersed.
14 Such hydrophone arrays find use as naval undersea warfare towed
15 arrays, or towed geophysical exploration arrays. In the latter
16 the arrays respond to artificially produced shocks of
17 predetermined character and location induced in the body of
18 water, and the response of the array to bottom return signals
19 are used to locate ocean bottom geophysical feature indicating
20 likely presence of an oil deposit. Yet further, a sensing
21 position on a fiber span 9 could be used to receive as an input
22 microphonic signals suitably imparted to the region of the
23 sensing position. The electromagnetic field sensing mode of
24 fiber span 9 could be used for monitoring electronic signals

1 along a telecommunication cable's span to localize malfunctions.
2 Responses of fiber span 9 to mechanical, pressure or thermal
3 strains can be used in systems for monitoring such strains.

4 The composite lightwave propagates up the optical fiber or
5 medium 9, passes through optical coupler, beamsplitter or
6 circulator, 7, to optical pathway, 11. Optical pathway, 11,
7 passes the backscattered, time-delay multiplexed, composite
8 lightwave, $E_b(t)$, to the optical receiver, 15.

9 Preferably, fiber 9 is of the relatively low cost,
10 conventional single-mode or multimode, fiber cable types.

11 Further it is preferable that fiber 9 have extruded thereon
12 a coating 12 of a material which enhances the longitudinal
13 strain which the fiber undergoes from a given radially, or
14 generally laterally, applied pressure wave strain. Materials
15 which provide such enhancement include extrudable thermoplastic
16 polymers (TPU's) or extrudable thermoplastic elastomers (TPE's)
17 which exhibit a combination of a low Young's modules (E) and a
18 low Poisson's ratio (σ). The Poisson's ration is preferably
19 below 0.5, which is the Poisson's ratio of natural rubber.

20 Examples of such materials include: (i) low density
21 polyethylene, having characteristic $E = 1.31 \text{ dynes/cm}^2 \times 10^{-10}$ and
22 $\sigma = 0.445$; and (ii) polystyrene, $E = 3.78 \text{ dynes/cm}^2$ and $\sigma = 0.35$
23 (values as reported in the paper, R. Hughes and J. Javzynski,
24 "Static Pressure Sensitivity Amplification in Interferometric

1 Fiber-Optic Hydrophones," Applied Optical/Vol. 19/ No. 1/ 1
2 January 1980).

3 An alternate embodiment of fiber 9, albeit involving
4 significantly greater cost per unit length of the fiber, is to
5 provide fiber in the more expensive form of a polarization
6 preserving or single polarization, optical fiber. The
7 polarization preserving fiber of this type holds the
8 backscattering light in a narrow range of polarization states so
9 that a substantially single RF signal 21 enters a single set 23
10 of correlators, reducing the complexity of the system. However,
11 in cases involving long surveillance lines this alternative
12 embodiment becomes expensive in cost of fiber.

13 The correlation code generator 53 creates a signal, $c(t)$,
14 that has a broad bandwidth. The broadband nature of the
15 correlation code is required to obtain the desired properties in
16 the signals autocorrelation function. The calculation and
17 definition of the autocorrelation function of any general signal
18 is well known and defined in signal processing literature. The
19 correlation code signal, $c(t)$, is so structured that its
20 autocorrelation function is highly peaked at zero delay, and is
21 very small away from zero delay. This criterion is well known
22 to those of skill in the art and is the essence of why the
23 correlation code has a broad bandwidth. Any signal that has the
24 desired autocorrelation function properties can be used as the

1 correlation code in the invention. There are many reasons for
2 choosing one correlation code over another: ease of creation;
3 autocorrelation properties; cost of creation hardware; cost of
4 correlation hardware; and effectiveness in producing spread
5 spectrum signal effects. According to the teaching of the
6 invention, the correlation code for the invention can be a
7 binary sequence with a desired transorthogonal autocorrelation
8 property (sometimes called a pseudonoise sequence), a
9 pseudorandom number (PRN) sequence with the such desired
10 autocorrelation property, chirps, or other types of signals
11 which provide correlations code having predicable non-repetitive
12 behavior. The foregoing list of types of sequence signals which
13 may be employed to modulate the carrier lightwave signal
14 includes both "binary pseudonoise sequences" and "pseudorandom
15 number (PRN) sequences." For purposes of construction of this
16 specification and the appended claims, these terms are employed
17 as they are defined under the listings "Pseudonoise (PN)
18 sequence (communication satellite)" and "Pseudorandom number
19 sequence" at pages 747 and 748 of the "IEEE Standard Dictionary
20 of Electrical and Electronic Terms" (Fourth Edition), which
21 listings are hereby incorporated herein by reference. Further
22 for purposes of construction of this specification and the
23 appended claims, it is deemed that "binary pseudonoise sequence"
24 is generic and "pseudorandom number sequence" is a species

1 thereof. Still further for purposes of construction of this
2 specification and its appended claims, both terms are deemed to
3 include analog signal forms of sequences as well as digital
4 signal forms.

5 It is to be appreciated that in addition to its correlation
6 encoding function, master correlating code generator 53 is a
7 source of a spectrum-spreading signal comprised of a spectrum-
8 spreading signal which produces an autocorrelation that is well
9 behaved. It has one dominate maxima at zero correlation delay,
10 and its spectrum is large enough to provide sampling of the said
11 optical fiber spatially along the length of the fiber 9 with a
12 resolution commensurate with a sub-length ΔZ of fiber span 9.
13 These characteristics enable segmentation of an optical fiber 9
14 of span length L into n segments in accordance with a
15 relationship

$$L < \Delta Z \cdot n. \quad (40)$$

16
17
18
19 In this relationship ΔZ is a segment length of the fiber span
20 whose length is one-half the distance traveled by light
21 propagating through one zero delay temporal time span of the
22 autocorrelation maxima, ΔT , such that C_L is the speed of light in

1 the said optical fiber and ΔT is approximately equal to the
2 reciprocal of the spread signal optical bandwidth.

3 An illustrative embodiment of generator 53 is a shift
4 register type pseudorandom number code generator, having n bits,
5 wherein a code is generated that satisfies said resolution
6 sublength and segment length relationship by choosing an
7 appropriate combination of the number of its bits and the clock
8 time.

9 The temporal length of the code sequence which is
10 reiteratively produced by generator 53 may be either less than
11 the time period for propagation of a lightwave to the remote end
12 of span and propagation back of a backscattering (i.e. distance
13 of flyback travel), or greater than this time period. It cannot
14 be equal to this period.

15 The predetermined timing base employed by the source of the
16 spectrum spreading signals, which determines the length of ΔZ
17 segment is so chosen to provide a positive enhancement to the
18 ratio of the power of back propagating Rayleigh scattering
19 effect P_R to the power of the forward propagated Rayleigh
20 scattering effect P_T , in accordance with the following equation:

21

$$22 \quad \frac{P_r}{P_t} [dB] = -70 + 10 \log_{10} (\Delta L) - \frac{\Delta Z}{100}. \quad (41)$$

1 b. Laser Phase Locking Means.

2 Refer to Figure 3. Local oscillator laser, 45, generates a
3 local oscillator lightwave. The local oscillator lightwave
4 propagates from local oscillator laser, 45, to optical coupler
5 or beamsplitter, 43. The optical coupler, 43, splits off the
6 smaller portion of power of the local oscillator lightwave into
7 optical pathway, 41. Optical path, 41, propagates the smaller
8 portion of the local oscillator lightwave to the phase locking
9 means optical receiver, 35. The larger portion of the power of
10 the local oscillator lightwave is split off by optical coupler
11 43, and passed to optical path 13. Optical pathway, 13,
12 propagates the larger portion of the local oscillator lightwave
13 to optical receiver, 15. The phase locking means optical
14 receiver, 35, receives and interferes the transmitter laser
15 lightwave from optical pathway, 39, and the local oscillator
16 lightwave from optical pathway 41. The receiver 35 interferes
17 the reference lightwaves from lasers 3 and 45 producing an
18 electrical output which is a radio frequency wave on electrical
19 pathway, 33. The electrical output, 33, provides an electronic
20 beat frequency which directly indicates the difference in
21 optical frequency and phase between lasers 1 and 45. Phase
22 locking circuitry 31, employing a conventional phase lock loop
23 mechanism, controls the difference in frequency between laser 1
24 and 45 and phase locks the two lasers to a fixed frequency and

1 phase relationship as indicated by the dashed line between
2 circuitry 31 and local oscillator laser 45. The radian
3 frequency difference is $\Delta\omega$ as discussed early in the text. The
4 purpose of the laser phase locking means is to insure that the
5 local oscillator lightwave traveling on optical path, 13, into
6 optical receiver, 15, has the proper phase and frequency
7 relationship to the composite lightwave on optical pathway, 11.
8 It is to be appreciated that the phase locking mechanism also
9 acts cooperatively with phase demodulator system 66 to be
10 described later herein. Conventionally, a common master clock
11 oscillator 311, Fig. 7 provides the timing base for both phase
12 locking circuitry 31 and an I & Q demodulator 300, FIG. 7.

13 Refer to Figure 3. The composite lightwave on optical path
14 11, is an input into optical receiver 15. The local oscillator
15 lightwave on optical path, 13, is also an input into optical
16 receiver, 15. The local oscillator and composite lightwaves are
17 interfered on photodetectors producing an electronic signal
18 which electronically represents the heterodyned optical
19 interference power between the two lightwaves. The resulting
20 composite radio frequency signal at output, 17, represents
21 electronically the composite lightwave signal on optical path,
22 11. The composite electronic receiver signal is passed from
23 optical receiver output, 17, through amplifier, 19, via
24 electronic path, 21, to the correlator system, 23. The local

1 oscillator lightwave on optical path, 13, is interfered with the
2 composite lightwave on optical path 11. The interference power
3 is photodetected in optical receiver, 15, by optically
4 interfering the composite back propagating lightwave on the
5 local oscillator signal. As one of the components of this
6 interfering action, there is produced a difference beat signal
7 which is a composite radio frequency representation of the
8 composite light wave on optical path, 11.

9 This interfering of the local oscillator output lightwave
10 13 and the composite back-propagating CW lightwave 11 provides
11 the translation of signal 11 from the optical domain to a CW
12 radio frequency (r.f.) composite difference beat signal 17. This
13 reduces the frequency of signal 15 into an electronically
14 processable signal frequency range. It is to be appreciated
15 that an important aspect of the present invention that the r.f.
16 composite difference signal produce by this translation action
17 includes having counterpart components of the aforesaid
18 components of the composite back-propagating lightwave signal,
19 with the phase states of these counterpart r.f. domain signals
20 the same as the phase states of the corresponding components of
21 the back-propagating lightwave.

22 In accordance with the present invention, lasers 3 and 45
23 are to have sufficiently stringent high performance capability
24 with respect to exactness of frequency to enable interference

1 effects therebetween and heterodyne detection of acoustic
2 perturbation signals incident to fiber 9 to produce beat
3 frequencies within the radio frequency (r.f.) range. Also in
4 accordance with the present invention, lasers 3 and 45 have
5 stringent performance criteria with respect to the phase
6 stability, or coherence, of their beams. They are to be
7 substantially coherent over at least a propagation path distance
8 substantially equal to twice the length, L, of sensing fiber 9.
9 For example, a commercially available non-planar, ring laser
10 (e.g. Lightwave Electronics Corp. Model 125) would be suitable
11 for an intruder sensing perimeter intrusion monitoring fiber 9
12 having a length of 8.0 km (approximately 5 miles). The laser
13 beam of this commercially available laser, which is in the near
14 infrared range, has a frequency of 227 terahertz, or 1319
15 nanometer wavelength, and has a frequency stability accurately
16 within one part in a billion over 1 millisecond period, or 5
17 Kilohertz in a 1 millisecond period.

18 It is to be appreciated that the provision of such
19 frequency and phase stability of lasers 3 and 45 enables
20 implementing the phase locking to produce a sufficiently small
21 non-zero radian phase locking circuitry 31. This in turn
22 enables lasers 3 and 45, under regulation by phase locking
23 circuitry 31, to provide a pair of beams which are phase locked
24 and with a "non-zero $\Delta\omega$ " sufficiently small to enable a

1 heterodyne-mode optical receiver to provide the desired beat
2 frequency outputs in the r.f. range. It is understood that
3 laser 45, optical receiver 35, circuitry 31 and beamsplitter 43
4 could be replaced with an apparatus applying the non-zero $\Delta\omega$ to
5 the beam from optical pathway 39 to give the same result. The
6 returned interrogation optical composite wave is defined in the
7 preceding subsection 3(a) "Optical Transmitter and Time-delay
8 Multiplexing Process" of this DESCRIPTION OF THE PREFERRED
9 EMBODIMENT.

10 In the preceding section (1) "Description of Underlying
11 Theories" of this DESCRIPTION OF THE PREFERRED EMBODIMENT there
12 is a definition of "non-zero $\Delta\omega$ " and a mathematical
13 demonstration of its importance in the heterodyne mode of
14 interfering. It makes it possible to use relatively simple
15 processes to avoid fading. By way of contrast, fading with the
16 "zero $\Delta\omega$ " homodyne mode of interfering would entail much more
17 difficult and less effective fade avoidance processes.

18 c. Correlation Time-Delay Demultiplexing.

19 Refer to Figure 3. The composite radio frequency signal on
20 electrical path, 21, is input into the correlator system, 23.
21 The correlator system delays the master correlation code
22 generator output, 51, an appropriate amount and correlates the
23 delayed correlation code with the composite radio frequency

1 signal. This produces electrical outputs $O_1, O_2 \dots O_n$ corresponding
2 to signals $S_1, S_2 \dots S_n$, in turn corresponding to spatial delays $L_1,$
3 $L_2 \dots L_n$. The spatial delays $L_1, L_2 \dots L_n$ are arbitrary and
4 programmable. The electrical output O_1 corresponds to $B(t, L_1)$
5 referred to in the preceding subsection 2(a).

6 The correlation process is well understood in the
7 literature. The signal that represents the backscattered
8 optical wave in array, 9, that is passed from the optical
9 receiver 15, to the correlator system 23, contains all of the
10 information for all sensors or channels $S_1, S_2 \dots S_n$ at once on the
11 electronic signal path 21 entering the correlator 23. Because
12 the backscattered composite signal is modulated with the
13 correlation code by modulator 5, the backscattered light is time
14 structured with the time structure of the correlation code.
15 Because the correlation code is selected to have special
16 autocorrelation code properties, the time structure of the
17 correlation codes allows an electronic representation of the
18 backscattered light at positions $L_1, L_2 \dots L_n$ to be obtained via the
19 correlation process in the correlator 23. In a preferred
20 embodiment of the invention the master code generator 53 is a
21 shift register type pseudorandom number (PRN) code generator and
22 each correlator of the set 23 would be a correlation type
23 demodulator herein later described in greater depth. Code

1 generator 53 may alternatively be embodied as a binary sequence
2 having transorthogonal autocorrelation properties (binary
3 pseudonoise sequence) and each correlator would then be a
4 correlation-type demodulator for demodulating a binary
5 pseudonoise sequence, whose implementation would be understood
6 by those of skill in the art. The correlator uses the reference
7 correlation code from correlation code generator, 53, which is
8 passed via electronic path 51 to the correlator, 23, as a
9 "golden ruler" enabling sorting out by temporal and spatial
10 domain demultiplexing electronic representations of the
11 backscattering optical signals at sensors or channels $S_1, S_2 \dots S_n$.
12 Various delayed versions of the correlation code are multiplied
13 by the composite signal with all of the sensor or channel
14 signals present simultaneously, from electronic path 21 so that
15 the electronic representations of the sensors or channels
16 $S_1, S_2 \dots S_n$ are output from the correlator, 23 on signals $O_1, O_2 \dots O_n$
17 with respect to the index.

18 Correlator system 23 is an electronic spread spectrum
19 signal de-spreader and temporal and spatial domain de-
20 multiplexer of the r.f. signal counterpart to the optical
21 composite signal. Its input is coupled to the amplified output
22 21 of the heterodyner and photodetector, and it is operative in
23 cooperation with said source of spectrum spreading signals to
24 perform a coherent signal correlation process upon the r.f.

1 counterparts of the aforesaid "one" and the aforesaid "still
2 another" components of the composite back-propagating CW
3 lightwave. This causes the de-spreading of the r.f. counterpart
4 of the optical reflected spread spectrum signal and causes the
5 temporal and spatial demultiplexing of the r.f. counterpart of
6 the "still another" component of the composite r.f. signal.
7 This processing provides signals which temporally and spatially
8 sort the said "still another" component into n virtual sensor
9 signal channels, or stated another way n of each of the ΔZ
10 length measurement regions, measuring the induced optical path
11 change at each of the n ΔZ -length segments of the optical fiber
12 span 9.

13 It will be appreciated that this sorting process is
14 accomplished by the autocorrelation properties of the spectrum-
15 spreading signal and by the time of flight of the optical
16 spectrum-spreading signal down to each n th reflection segment
17 and back to the heterodyne optical receiver 15. A delayed
18 replica of the spectrum-spreading signal is correlated against
19 the r.f. signal counterpart of the optical composite back-
20 propagating signal, thereby segmenting the optical fiber into n
21 independent segments, or virtual sensors, via the time of flight
22 of the optical composite back-propagating signal and the
23 autocorrelation function of the transmitted spectrum-spreading
24 signal.

1 It is to be appreciated that system 2 is operating in the
2 spread spectrum transmission and reception mode. Namely, by
3 providing optical interrogation light wave, $E_1(t)$, with
4 modulation by the correlation code, $c(t)$, the continuous wave
5 carrier signal is temporally structured into a spread spectrum
6 interrogation lightwave which continuously reiterates
7 autocorrelatable code sequences. Then after correlation system
8 provides an appropriate time of delay the correlator system 26
9 correlates the backscattered light wave $E_b(t)$ with the same
10 output, $c(t)$, of code generator 53, de-spreading the spread
11 spectrum signal.

12 In accordance with well known communication electronics
13 theory this has the effect of increasing signal output of the
14 ROSE sensor system while the noise bandwidth remains the same.
15 In temporally and spatially sorting the r.f. counterpart of the
16 aforesaid "still another" component of the composite back-
17 propagation lightwave, the aforesaid "another" component of
18 undesired noises, such as reflections from couplers in fiber
19 span 9, are materially attenuated.

20 More particularity, in accordance with this well known
21 theory, the signal-to-noise ratio (SNR) is enhanced by
22 considerable attenuation of noise mechanisms in frequency ranges
23 outside of center frequency lobe of the autocorrelation function

1 and outside the pair of first side lobes to one and the other
2 side of the center frequency lobe.

3 An illustrative embodiment of electronic spread spectrum
4 signal de-spreader and spatial de-multiplexer for cooperation
5 with the previously described shift register type PRN code
6 generator may comprise a series of n like-shift register code
7 generators respectively receiving the spectrum spreading signal
8 through a corresponding series of n feed channels which cause
9 delays which incrementally increase by an amount of time bearing
10 a predetermined relationship to the fiber span length, and C_L ,
11 the speed of light through the fiber. The composite r.f. signal
12 is fed to a corresponding series of n multipliers connected to
13 receive as the other multiplier the codes generated by the
14 respective de-spreader and demultiplexer to thereby provide the
15 de-spread and de-multiplexed signal.

16 d. Heterodyne Phase Demodulation.

17 Refer to Figure 3. After the composite radio frequency
18 signal on electrical path 21 is correlation time-delay
19 demultiplexed by the correlator system, 23, the plurality (which
20 upwardly may include a very large number, for instance 5,000) of
21 outputs $O_1, O_2 \dots O_n$, on the plurality of electrical paths 61, 63
22 and 65 respectively are phase demodulated by a plurality of
23 individual phase demodulations in the phase demodulator system,
24 66. The outputs of the phase demodulator system, 66, are the

1 corresponding plurality of electrical paths 71, 73, and 75. The
2 phase demodulator outputs 71, 73, and 75 correspond to the
3 correlator outputs ($O_1, O_2 \dots O_n$) 61, 63 and 65 respectively, and
4 to the corresponding plurality of corresponding signals $S_1, S_2 \dots$
5 S_n respectively corresponding to spatial delays $L_1, L_2 \dots L_n$
6 respectively. The outputs 71, 73, and 75 electronically
7 indicate (with tens of kilohertz potential bandwidth) the phase
8 states of optical signals $S_1, S_2 \dots S_n$. In particular, output 71
9 is proportional to the temporal phase Φ_1 of $B(t, L_1)$ hereinbefore
10 discussed in subsections 1(b) "Correlation or Time-delay
11 Multiplexing" and 3(c) "Correlation Time-Delay Demultiplexing"
12 of this DESCRIPTION OF THE PREFERRED EMBODIMENT. The phase
13 demodulator outputs 73 and 75 indicate the temporal phase states
14 Φ_2 and Φ_n of $B(t, L_2)$ and $B(t, L_n)$ respectively.

15 e. Fading Free Polarization Processing

16 Preferably system 2 further includes polarization signal
17 characteristic processing functions (not shown), which are used
18 together with the previously described feature that the
19 heterodyning function provides in reducing fading, of the
20 backscattering signal, $E_b(t)$. These polarization processing
21 functions are disclosed in the commonly assigned U.S. Patent No.
22 6,043,921 entitled "Fading-Free Optical Phase Rate Receiver,"
23 hereby incorporated herein in its entirety. The optical

1 heterodyning feature which provides benefit in reducing fading
2 includes: (i) cooperation of phase locked lasers 3 and 45 in the
3 formation of the optical interrogation light wave, $E_1(t)$, applied
4 to optical fiber 9, or other linearly extended light propagation
5 medium producing Rayleigh effects backscattering, and (ii) the
6 manipulation of this by optical receiver 15 to provide the
7 composite electronic receive signal as optical receiver output
8 17. This takes advantage of the feature of more favorable
9 Heterodyne fading conditions in a way, in which polarization and
10 phase state signal fading is materially reduced in the detected
11 backscattered light wave $E_b(t)$. The electronic decoding module
12 700 of Patent 6,043,921 is substantially an equivalent to the
13 correlator system herein. However, the system disclosed in
14 Patent 6,043,921 for implementing polarization fading reduction
15 (if not substantially eliminating fading) is a generalized stand
16 alone system for processing any optical phase signal having
17 temporally varying polarization, phase, and phase frequency. It
18 must be adapted for application to system 2 by appropriate
19 integration into system 2 included the two following alternative
20 approaches.

21 One approach for such adaptation passes the fade-free
22 optical phase rate (FFOPR) photoreceiver RF signal to the
23 correlator 23, performs the correlation on the RF signal and
24 completes the Phase Demodulation by In phase and Quadrature

1 phase (hereinafter I & Q) demodulating the correlated RF signal
2 into outputs. This method creates low bandwidth I & Q
3 components and therefore requires low bandwidth analog-to-
4 digital converters (implying a requirement for a large number of
5 analog RF correlation electronic components). This RF
6 correlator approach requires two correlator circuits for every
7 virtual sensor element, or spatial channel, along fiber 9. One
8 correlator is needed for the vertical polarization RF signal
9 path and one correlator is needed for the horizontal
10 polarization RF signal path.

11 Another approach applies the I & Q demodulator of Figure 7
12 of the U.S. Patent 6,043,921 prior to correlation. This
13 approach therefore correlates a wideband set of four I & Q
14 signals. One I, Q, set is for horizontal polarization and the
15 other I, Q, set is for the vertical polarization. In this case
16 the I & Q signals are the I & Q signals for the whole virtual
17 array rather than for one virtual sensor element of the array.
18 Four correlators are required for each sensor element. One
19 correlator is applied to each of the four wide bandwidth I & Q
20 signals for each virtual sensor element. This second approach
21 requires very wideband analog-to-digital converters, but allows
22 digital correlators to be used instead of analog RF correlators.
23 The RF correlator or first approach requires far more analog to
24 digital converters and RF electronics. The digital correlator

1 approach enables the correlators to be implemented by the
2 digital approaches of massively integrated logic circuits and/or
3 programmed processors, requiring far more digital logic, but
4 substantially reducing the r.f. electronics and number analog-
5 to-digital converter units in the system.

6 f. Phase Differencing

7 Refer to Figure 3. The plurality (which upwardly may
8 include a very large number, for instance 5,000) of signals
9 indicating the phase states $\Phi_1, \Phi_2 \dots \Phi_n$ on electrical paths 71, 73
10 and 75, respectively, are input into the phase differencer, 99.
11 The phase differencer forms a corresponding plurality of outputs
12 91, 93 and 95 which are arbitrarily and programmably assigned as
13 the subtractions of any two pairs of phase signals Φ_j and Φ_k
14 (where j and k are selected from 1, 2 ... n).

15 Each of the programmably selectable pairs of differenced
16 phase signals form a signal $\Delta\Phi_{kj}$ which is spatially bounded
17 within the region of the fiber between lengths L_j and L_k . The
18 phase differencer therefore produces differential phase outputs
19 corresponding to a set of programmable length and position
20 virtual sensors.

21 Stated another way, each programmable selection of pairs of
22 phase signals forms a virtual spatial differential sensor which
23 senses the difference between the phases of the $\Delta\omega$ output of the
24 photodetector sub-system (which is the subject of the next

1 subsections) in receiver 15. Each $\Delta\omega$ is an r.f. difference beat
2 signal representative of the aforesaid "still another" component
3 of the composite back-propagating CW lightwave signal which
4 passes from the launch end of fiber span 9 to directional
5 coupler 7. These signals from each pair therefore represent
6 signals of virtual spatial differential sensors along fiber span
7 9. As a result of the choice of pairs being selectively
8 programmable these virtual sensor can be employed to implement
9 adaptive apertures in processing signal incident the fiber span.
10 This feature would be useful, for example, in enabling security
11 system operators to classify objects causing acoustic pressure
12 wave signals incident up a fiber span 9 used as a perimeter
13 intrusion monitoring line.

14 g. Optical Detector Sub-System.

15 The optical receivers 15 and 35, Figs 3, 4 and 5, are
16 comprised of photodetector sub-systems. Any of the many well
17 known photodetecting techniques and devices may be employed.
18 Possible implementation of the photodetection sub-systems will
19 now be discussed.

20 Refer to Figure 4. Like parts correspond to like numbers.
21 Optical signals enter the photodetector sub-system via optical
22 paths 101 and 103 which are extensions of the paths 11 and 13 in
23 the case of receiver 15, and (not shown) of paths 39 and 44 in
24 the case of subsystem 35. The optical signals are equally split

1 by optical coupler or beamsplitter, 105. The optical signal on
2 path 107 is composite signal comprised of half the optical power
3 of path 101 and half of the optical power arriving on path 103.
4 The optical signal on path 107 is illuminated on optical
5 detector 111. The photo-current of optical detector 111 flows
6 into electrical conductor 115. Likewise, the optical signal on
7 path 109 is comprised of half the optical power on path 101 and
8 half of the optical power on path 103. The optical signal on
9 path 109 is illuminated on optical detector 113. The photo-
10 current of optical detector 113 flows out of electrical
11 conductor 115. Therefore the photo-currents of optical
12 detectors 111 and 113 are subtracted at electrical conductor or
13 node 115.

14 Photo-detectors 111 and 113 are precisely matched in
15 responsivity. The differential photocurrent on electrical
16 conductor 115 is input into pre-amplifier 117, amplifier and is
17 passed to electrical output 119. The differential nature of the
18 photo-detection rejects either of the self-optical interference
19 power of the signals on paths 101 and 103 and receives only the
20 cross-interference power between the two optical signals on
21 paths 101 and 103. This particular optical detector
22 architecture is called a balanced heterodyne optical detection
23 scheme. The scheme is 3 dB more sensitive than all other

1 heterodyne optical detection methods and offers the distinct
2 advantage of rejecting local oscillator noise.

3 Refer to Figure 5. Figure 5 illustrates an alternative
4 photo-detection scheme to Figure 4. Lightwaves enter the
5 receiver at paths 101 and 103. The optical coupler or
6 beamsplitter 105 combines the lightwaves on paths 101 and 103
7 into a composite lightwave on path 107. The composite lightwave
8 on path 107 illuminates optical detector 111. The photo-current
9 of optical detector caused by the self-interference and cross
10 interference of lightwaves originating from optical paths 101
11 and 103 passes through conductor 115a, is amplified by pre-
12 amplifier 117 and is passed to electrical output 119.

13 The optical detector sub-system of Figures 4 and 5
14 correspond to optical receivers 15 or 35 of Figure 3. Paths 101
15 and 103 correspond to 11 and 13 and output 119 corresponds
16 outputs 17 in optical receiver 15. Paths 101 and 103 correspond
17 to 39 and 41 and output 119 corresponds to output 33 in optical
18 receiver 35. Either of the photo-detection schemes of Figures 4
19 or 5 can be used for the optical receivers 15 or 35. However,
20 the photodetection scheme of Figure 4 is preferred.

21 h. Programmable Correlator System

22 Refer to Figure 6. The composite radio frequency signal,
23 or r.f. composite reference beat signal, which electronically
24 represents the received time-delay multiplexed optical signal,

1 or composite back-propagation CW lightwave, $E_b(t)$, is input into
2 the correlator system, 23, at electrical input 21. The
3 composite radio frequency signal is n-way split with power
4 splitter 203 into a plurality (which upwardly may include a very
5 large number, for instance 5,000) of electronic pathways
6 including 211, 213 and 215. the master correlation code, $c(t)$,
7 is input into the correlator system, 23, at electrical input 54.
8 The correlation code is distributed to such a plurality of
9 programmable delay circuits including 221, 223 and 225. Each
10 programmable delay circuit delays the master correlation code by
11 the delay required to decode/demultiplex each time-delay
12 multiplexed channel. The plurality of programmable delay
13 circuits including 221, 223 and 225 output a plurality of
14 delayed correlation codes including those on electrical pathways
15 231, 233, and 225 respectively. The corresponding plurality of
16 delayed correlation codes including those on electrical pathways
17 231, 233 and 235 are multiplied by a corresponding plurality of
18 multipliers (or balanced mixers) including 241, 243 and 245,
19 respectively, by the radio frequency signal on the plurality of
20 electronic pathways including 211, 213 and 215 which are
21 amplified by a corresponding plurality of amplifiers including
22 261, 263 and 265, respectively, to produce the corresponding
23 plurality of outputs including O_1 , O_2 , and O_n (on lines 61, 63
24 and 65) respectively. Each of the outputs therefore produces

1 the corresponding demultiplexed signal which is time-gated by
2 the corresponding time-delay of the correlation code. The
3 correlator system 23 of Figure 6 is an example implementation of
4 the correlation system, 23, of Figure 3.

5 The output O_1 corresponds to signal $B(t, L_1)$ which is
6 hereinbefore discussed in subsections 2(a) "ROSE Optical Phase
7 Sensor Interrogation Enables Sensor System" and 3(c)
8 "Correlation Time-Delay Demultiplexing" of this DESCRIPTION OF
9 THE PREFERRED EMBODIMENT. The output $O_1, O_2 \dots O_n$ on lines 61, 63
10 and 65, respectively, correspond to signals $S_1, S_2 \dots S_n$ which in
11 turn are based upon the spatial delay associated with distance
12 $L_1, L_2 \dots L_n$ indicated in Figure 3. These spatial delays are based
13 on the time of propagation for flyback travel along these
14 distances, which are arbitrary and programmable. The time delay
15 multiplexing of the optical signals comprising the composite
16 back-propagating optical signal on path 11, Figure 3, arise from
17 a plurality (which upwardly may include a very large number, for
18 instance 5,000) of spatial locations causing a like plurality of
19 time-delays. The correlator system spatially separates the
20 components of the r.f. composite difference beat signal into
21 channels which each uniquely represent an optical signal at a
22 single spatial location.

1 The correlator system allows the spatial sampling of the
2 optical signals so that a virtual array can be formed along the
3 fiber span 9 on Figure 3.

4 i. Phase Demodulation System

5 The embodiment of phase demodulator system, 66, of Figure
6 3, has two uses in system 2. It either: (i) receives the
7 outputs of the just described r.f. correlator subsection 23, or
8 (ii) is part of the integration of the polarization fading
9 reduction system of U.S. Patent 6,043,921 (as discussed in the
10 preceding subsection 2(e) "Fading-Free Polarization Processing"
11 of this DESCRIPTION OF THE PREFERRED EMBODIMENT. Refer to
12 Figure 7. The phase demodulation system, 66, is comprised of a
13 plurality (which upwardly may include a very large number, for
14 instance 5,000) of phase demodulators, 81, 83 and 85. The
15 inputs to the plurality of phase demodulators, 61, 63 and 65
16 (the correlator outputs O_1 , O_2 ... O_n discussed previously) are
17 phase demodulated with phase demodulators 81, 83 and 85
18 respectively. The outputs of these demodulators are passed on
19 electrical pathways 71, 73 and 75 respectively.

20 Refer to Figure 8. An example block diagram of any one of
21 the just discussed phase demodulators 81, 83 and 85 is shown as
22 part 300. The input electrical path 301 corresponds to any one
23 of electrical path 61, 63, 65, etc. of the plurality of phase
24 demodulators. The output electrical path 319 corresponds to any

1 one of electrical path 71, 73, 75, etc. of the plurality of
2 phase demodulators. A correlation system output such as O_1 , O_2
3 or O_n is passed via electrical path 301 into a bandpass filter
4 303. The bandpass filter 303 passes only a band of radian
5 frequencies in the vicinity of $\Delta\omega$ so that only $B(t, L_m)$ passes
6 through the filter (where m is an integer corresponding to the
7 particular channel). The band passed signal passes from 303 via
8 electrical path 305 to amplitude control 307. Amplitude control
9 307 is either an analog automatic gain control circuit, an
10 electronic clipper circuit, or a combination thereof. The
11 amplitude control 307 removes amplitude variations due to
12 polarization fading or other types of signal fading. Because
13 the signal, $B(t, L_m)$ is a result of a heterodyne interference, the
14 phase remains the same after clipping. It is to be appreciated
15 that other phase demodulation schemes for fiber optic signals
16 use a phase carrier technique which does not allow the clipping
17 operation. Clipping is a preferred amplitude control mechanism.
18 The amplitude control 307 passes an amplitude stabilized signal
19 via electrical path 309 to I & Q demodulator 311. The I & Q
20 demodulator removes the carrier, that is it shifts the center
21 radian frequency of the amplitude stabilized $B(t, L_m)$ from $\Delta\omega$ down
22 to zero. The I & Q demodulator outputs a voltage proportional
23 to $\cos(\Phi_m)$ on electrical path 313 and a voltage proportional to
24 $\sin(\Phi_m)$ on electrical path 315. The $\cos(\Phi_m)$ and $\sin(\Phi_m)$

1 proportional voltages on electrical paths 313 and 315
2 respectively are converted in an output signal proportional to Φ_m
3 on electrical path 319 by the phase detector 317.

4 Reviewing the previous discussion, the plurality of phase
5 demodulators 81, 83 and 85 of Figure 7 each function like the
6 block diagram of 300 on Figure 8. The plurality (which upwardly
7 may include a very large number, for instance 5000) of phase
8 demodulators 300 convert to a like plurality of signals $B(t, L_1)$,
9 $B(t, L_2) \dots B(t, L_n)$ into a like plurality of signals proportional
10 to $\Phi_1, \Phi_2 \dots \Phi_n$ which correspond to optical signals $S_1, S_2 \dots S_n$.

11 j. I & Q Demodulator.

12 An example implementation of the I & Q demodulator 311 of
13 Figure 8 will now be presented. Refer to Figure 9. An amplitude
14 stabilized $B(t, L_m)$ signal (originating from the amplitude control
15 307 of Figure 8) is passed on electrical path 309 to a power
16 splitter 403. Half of the signal power exiting from power
17 splitter 403 is passed to analog mixer, balanced mixer, Gilbert
18 cell or analog multiplier 413 via electrical path 411. The
19 other half of signal power exiting from power splitter 403 is
20 passed to analog mixer, balanced mixer, Gilbert cell or analog
21 multiplier 423 via electrical path 421.

22 The reference oscillator 451 generates an electronic wave
23 proportional to $\cos(\Delta\omega t)$. As noted earlier herein, this
24 reference oscillator is also the oscillator employed in the

1 conventional phase lock mechanism establishing the fixed phase
2 relationship between the frequencies of primary laser 3 and
3 local oscillator laser 45 whose differences in frequency, ΔW ,
4 are of a very low order. In accordance with known principles of
5 heterodyning lightwaves having fixed phase relationships,
6 heterodyning these signals can produce a difference beat signal
7 small enough to be in the r.f. signal range, but with the
8 frequency difference sufficiently high to provide the
9 heterodyning with a band pass allowing transforming a given
10 binary code rate into corresponding code components of the beat
11 signal, such as the code rate of the PRN code sequence produced
12 by PRN code generator 53. This reference oscillator wave is
13 passed from the reference oscillator 451 via the electrical path
14 453 to amplifier 455. The wave is amplified by amplifier 455
15 and passed to hybrid coupler 459 via electrical path 447. The
16 hybrid coupler splits the amplified reference oscillator
17 electronic wave into two components one proportional to $\cos(\Delta\omega t)$
18 on electrical path 417 (providing the "I", or In-phase
19 reference); and one proportional to $\sin(\Delta\omega t)$ on electrical path
20 427 (providing the "Q", or Quadrature-phase reference).

21 The In-phase reference on electrical path 417 is multiplied
22 (or frequency mixed) with the signal on electrical path 411 by
23 multiplier 413 to produce the output on electrical path 415.
24 The signal on electrical path 415 is amplified by amplifier 431

1 and passed to electronic lowpass filter 435 via electrical path
2 433. The lowpass filter 435 removes high frequency components
3 of the multiplication or frequency mixing process and results in
4 an output at electrical path 313 which is proportional to
5 $\cos(\Phi_m)$.

6 The Quadrature-phase reference on electrical path 427 is
7 multiplied (or frequency mixed) with the signal on electrical
8 path 421 by multiplier 423 to produce the output on electrical
9 path 425. The signal on electrical path 425 is amplified by
10 amplifier 441 and passed to electronic lowpass filter 445 via
11 electrical path 443. The lowpass filter 445 removes high
12 frequency components of the multiplication or frequency mixing
13 process and results in an output at electrical path 315 which is
14 proportional to $\sin(\Phi_m)$.

15 k. Phase Detector

16 Example implementations of the phase detection 317 of
17 Figure 8 will now be presented. Refer to Figure 10. An example
18 digital phase detector implementation, 317, is shown in the
19 block diagram. The signal proportional to $\cos(\Phi_m)$ on electrical
20 path 313 is converted to a digital code or number by analog-to-
21 digital converter (hereafter, A/D) 513. The digital number
22 proportional to $\cos(\Phi_m)$ is input into the digital signal
23 processor 501 via electrical path 515. The signal proportional
24 to $\sin(\Phi_m)$ on electrical path 315 is converted to a digital code

1 or number by A/D 523. The digital number proportional to $\sin(\Phi_m)$
 2 is input into the digital signal processor, 501, via electrical
 3 path 525. The digital signal processor converts the numbers
 4 proportional to $\sin(\Phi_m)$ and $\cos(\Phi_m)$ into a number proportional to
 5 Φ_m as follows.

6 Suppose the constant of proportionality for the $\sin(\Phi_m)$ and
 7 $\cos(\Phi_m)$ is V_m . Then the digital signal processor can optimally
 8 select estimates of Φ_m and V_m to minimize the calculated error
 9 function:

10

$$11 \quad \varepsilon(\hat{\Phi}_m, \hat{V}_m) = \left((V_m \cos(\Phi_m) - \hat{V}_m \cos(\hat{\Phi}_m))^2 + (V_m \sin(\Phi_m) - \hat{V}_m \sin(\hat{\Phi}_m))^2 \right) \quad (42)$$

12

13 The digital signal processor can also calculate Φ_m directly
 14 by taking the inverse tangent function or the inverse cotangent
 15 function:

16

$$17 \quad \Phi_m = a \tan \left(\frac{V_m \sin(\Phi_m)}{V_m \cos(\Phi_m)} \right) = a \cot \left(\frac{V_m \cos(\Phi_m)}{V_m \sin(\Phi_m)} \right) \quad (43)$$

18

19 If desired, the digital signal processor can also implement
 20 the differentiate and cross multiply (hereafter DCM) algorithm.
 21 The DCM method is as follows. The digital representation of the
 22 signals proportional to $\sin(\Phi_m)$ and $\cos(\Phi_m)$ are temporally

1 differentiated and cross multiplied by the non-differentiated
 2 signals. The result $U_m(t)$ is integrated to produce the desired
 3 output, Φ_m . Mathematically, this algorithm is:

$$\begin{aligned}
 U_m(t) &= V_m \sin(\Phi_m) \frac{\partial}{\partial t} (V_m \cos(\Phi_m)) - V_m \cos(\Phi_m) \frac{\partial}{\partial t} (V_m \sin(\Phi_m)) \\
 U_m(t) &= V_m^2 ((\cos(\Phi_m))^2 + (\sin(\Phi_m))^2) \frac{\partial \Phi_m}{\partial t} \\
 U_m(t) &= V_m^2 \frac{\partial \Phi_m}{\partial t} \\
 \Phi_m &= \frac{1}{V_m^2} \int U_m(t) dt.
 \end{aligned}
 \tag{44}$$

6
 7 The digital signal processor 501 converts the signals arriving
 8 on electrical paths 515 and 525 into a digital output
 9 proportional to Φ_m on electronic path 503. Optionally, the
 10 digital output is passed on electronic path 505 to some other
 11 data sink such as a computer memory. The digital signal
 12 proportional to Φ_m on electronic path 503 is converted back to an
 13 analog signal on electrical path 319 by digital-to-analog
 14 converter 507. By way of a summarization, the example digital
 15 phase detector 317 accepts inputs 313 and 315 which originate
 16 from the I & Q demodulator, 311, of Figure 8, and the digital
 17 phase detector 317 outputs the phase signal Φ_m on electrical path
 18 319. Optionally, any of other well-known implementations of
 19 digital phase detectors may be employed.

1 Refer to Figure 11. An example analog phase detector
2 implementation, 317' is shown in the block diagram. The example
3 analog phase detector 317' shown in Figure 11 implements an
4 analog version of the DCM algorithm discussed in the previous
5 text. The signal proportional to $\cos(\Phi_m)$ on electrical path 313
6 is input into analog temporal differentiator 613 and analog
7 multiplier 617. The signal proportional to $\sin(\Phi_m)$ on electrical
8 path 315 is input into analog temporal differentiator 623 and
9 analog multiplier 627. The differentiated cosine term on signal
10 path 625 is multiplied by the sine term on electrical path 315
11 by analog multiplier 627 producing the signal on electrical path
12 629. The differentiated sine term on electrical path 615 is
13 multiplied by the cosine term on electrical path 313 by analog
14 multiplier 617 producing the signal on electrical path 619. The
15 signals on electrical paths 619 and 629 are applied as inputs to
16 differential summer 631. The output of differential summer on
17 electrical path 633, which is the result of the differentiated
18 sine and cosine product being subtracted from the differentiated
19 cosine and sine product, corresponds to $U_m(t)$ of the DCM
20 discussion. The signal on electrical path 633 is integrated by
21 analog integrator 635 to produce the analog phase detector
22 output proportional to Φ_m on electrical path and output 319. By
23 way of summarization, the example analog phase detector 317
24 accepts inputs 313 and 315 which originate from the I & Q

1 demodulator 311 of Figure 8, then the analog phase detector
2 outputs the phase signal Φ_m on electrical path 319. Optionally,
3 any of other well-known implementations of analog phase
4 detectors may be employed.

5 1. Programmable Phase Difference

6 The example programmable phase differencer implementation
7 shown as part 99 of Figure 12 corresponds to part 99 shown as a
8 block in Figure 3. Refer to Figure 12. The plurality (which
9 upwardly may include a very large number, for instance 5,000) of
10 demodulated signals proportional to optical signal phases $\Phi_1, \Phi_2 \dots$
11 Φ_n are input into the programmable phase signal switching and
12 routing network 701 via electrical paths 71, 73 and 75,
13 respectively. Network 701 programmably selects on a basis of
14 timed relation to code generator 53 and routes on a basis of
15 conventional "hold-in memory" and "transfer-from-memory", a
16 plurality (which upwardly may include a very large number, for
17 instance 5,000) of pairs of phase signals onto a plurality
18 (which upwardly may include a very large number, for instance
19 5,000) of pairs of electronic paths 711 and 713, 731 and 733 and
20 751 and 753. The plurality of routed pairs of phase signals are
21 applied to the corresponding of subtracters 715, 735 and 755 as
22 shown on Figure 12. The plurality of phase pairs on electronic
23 pairs of paths 711 and 713, 731 and 733, and 751 and 753 are
24 subtracted by subtracters 715, 735 and 753, respectively, and

1 the differential signal are outputted on a corresponding
2 plurality of electrical paths 91, 93 and 95 respectively. The
3 following description focuses on the differencing channel output
4 on electrical path 91, it being understood that the modes of
5 operation of other differencing channels in network 701 are the
6 same. Programmable phase switching and routing network 701
7 selects one of the phase signals on one of the plurality of
8 electrical paths 71, 73 or 75 and routes the signal to
9 electrical path 711. The signal on electrical path 711 is
10 selected to be proportional to Φ_j (where j is of the set 1,2 ...
11 n). Network 701 also selects another of the phase signals on
12 one of the other of the plurality of electronic paths 71, 73 or
13 75 and routes the signal to electrical path 713. The signal of
14 electrical path 713 is selected to be proportional to Φ_k (where k
15 is of set 1,2 ... n). The signal on electrical path 711 is
16 subtracted from the signal on electrical path 713 by subtracter
17 715. The output of subtracter 715 is passed on via electrical
18 path 91 and is proportional to $\Delta\Phi_{kj}$ hereinabove discussed in
19 subsection 3(f) "Phase Differencing" of this DESCRIPTION OF THE
20 PREFERRED EMBODIMENT. Employing this mode, network 701
21 programmably makes selection from optical signal phases $\Phi_1, \Phi_2 \dots$
22 Φ_n to provide other differential phase outputs on electrical
23 paths 91, 93 and 95. This may include a very large number of

1 differential phase signals, for instance 5000. As an
2 alternative to the just described type of circuitry employing
3 subtracters 715, 735 and 755 any of other well-known forms of
4 producing a differential signal may be employed.

5 m. An Alternative Viewpoint of the Partitioning of
6 System 2.

7 As an alternative to the viewpoint inferable from the
8 preceding sequence discussing Figure 3, system 2 may be
9 considered as partitioned into: (i) an optical network for
10 illuminating an optical fiber sensing span, or other light
11 propagation medium sensing span, and retrieving back propagating
12 portions of the illumination; and (ii) a photoelectronic network
13 for establishing virtual sensors at predetermined locations
14 along the span and picking up external physical signals incident
15 to, or impinging upon, the sensors.

16 In general, the optical network for the illumination of,
17 and for the retrieval of back-propagation from, fiber span 9
18 comprises transmitter laser 3, directional optical coupler 7,
19 and optical fiber, or other light propagation medium 9.

20 The photoelectronic network for establishing virtual
21 sensors and picking up signals therefrom generally comprises two
22 subdivisions. One subdivision provides a cyclically reiterative
23 autocorrelatable form of modulation of the lightwave
24 illuminating fiber span 9. This modulation is in the form

1 reiterated sequences having autocorrelatable properties. The
2 other subdivision takes the retrieved back propagation and
3 performs a heterodyning therewith to obtain an r.f. beat signal.
4 It then picks up the signal from the virtual sensors by
5 autocorrelation and further processes it into more useful forms.

6 In general, the subdivision providing the cyclical
7 reiterative modulation of sequences illuminating fiber span 9
8 comprises master correlation code generator 53 (via one of its
9 electrical pathway outputs) and optical modulator 5.

10 In general, the subdivision for performing heterodyning
11 with and picking up of virtual sensor signals from the retrieved
12 back propagation from fiber span 9 includes local oscillator
13 laser 45, and the network which phase locks transmitter laser 3
14 and local oscillator 45, and a sequence of elements which
15 perform processing upon the retrieved back propagation. The
16 phase locking network comprises beamsplitter 4, phase locking
17 means optical receiver 35, phase locking circuitry 30, and
18 optical coupler 43. First in the sequence of processing
19 elements is an optical receiver 15 which photodetects
20 interference power "derived" by heterodyning the back propagated
21 illumination portion retrieved from fiber span 9 with the output
22 of a local oscillator 45. Lasers 3 and 45 are operated with a
23 frequency difference to produce an r.f. beat signal, ΔW . Then
24 correlation system 23 receives as one of its inputs another

1 electrical pathway output from master correlation code generator
2 53, and provides a series of channels which in turn respectively
3 provide predetermined time delays in relation to the timing base
4 of cyclic reiterative code generator 53, to perform a series of
5 autocorrelations of the respectively delayed inputs from code
6 generator 53 with the signal ΔW . This picks up r.f. signals
7 respectively representative of the affects in the lightwave
8 domain of the external physical signals incident upon the
9 respective virtual sensor. Phase demodulator system 66 provides
10 a linear phase signal derived from such r.f. signals
11 representative of optical signals at the respective virtual
12 sensors. Programmable phase differencer 99 processes pairs of
13 these linear phase signals occurring across segments of fiber
14 span 9 between programmably selected pairs of the virtual
15 sensors.

16 Following is another overview description which more
17 particularly calls attention to an aspect of the invention that
18 the system elements which perform the autocorrelation enable
19 providing an output in the form of an r.f. counterpart of a
20 lightwave time-domain reflectometry output of signals incident
21 to the virtual sensors as lightwave time domain reflectometry
22 outputs A CW lightwave modulated by a continuously reiterated
23 binary pseudorandom code sequence is launched into an end of a
24 span of ordinary optical fiber cable. Portions of the launched

1 lightwave back propagate to the launch end from a continuum of
2 locations along the span because of innate fiber properties
3 including Rayleigh scattering. This is picked off the launch
4 end and heterodyned to produce an r.f. beat signal. The r.f.
5 beat signal is processed by a plurality (which can be thousands)
6 of correlator type binary pseudonoise code sequence demodulators
7 respectively operated in different delay time relationships to
8 the timing base of the reiterated modulation sequences. The
9 outputs of the demodulators provide r.f. time-domain
10 reflectometry outputs representative of signals (e.g., acoustic
11 pressure waves) incident to virtual sensors along the fiber at
12 positions corresponding to the various time delay relationships.

13 Following is still another overview description which more
14 particularly calls attention to an aspect of the invention that
15 the system elements performing the autocorrelation enable
16 detection of unique spectral components representing a phase
17 variations of external signals incident to the virtual sensors.
18 A CW lightwave modulated by a continuously reiterated
19 pseudorandom code sequence is launched into an end of a span of
20 ordinary optical fiber cable. Portions of the launched
21 lightwave back propagate to the launch end from a continuum of
22 locations along the span because of innate fiber properties
23 including Rayleigh scattering. This is picked off the launch
24 end and heterodyned producing an r.f. beat signal. The r.f.

1 beat signal is processed by a plurality (which can be thousands)
2 of correlator type pseudonoise code sequence demodulation and
3 phase demodulator units, operated in different time delay
4 relationships to the timing base of the reiterated modulation
5 sequences. These units provide outputs representative of phase
6 variations in respective unique spectral components in the r.f.
7 beat signal caused by acoustic, or other forms of signals,
8 incident to virtual sensors at fiber positions corresponding to
9 the various time delay relationships.

10 Following is yet another overview description which more
11 particularly calls attention to an aspect of the invention that
12 a pair of the different delay time relationships of the
13 autocorrelation system elements are effective to establish a
14 virtual increment of the optical fiber span, and that a
15 subtracter circuit of phase differencer 99 enables representing
16 the differential phase signal across the virtual increment. A
17 CW lightwave modulated by a continuously reiterated pseudorandom
18 (PN) code sequence is launched into an end of a span of ordinary
19 optical fiber cable. Portions of the launched lightwave back
20 propagate to the launch end from a continuum of locations along
21 the span because of innate fiber properties including Rayleigh
22 scattering. This is picked off the launch end and heterodyned
23 producing an r.f. beat signal. The r.f. beat signal is
24 processed by a plurality (which can be thousands) of correlator

1 pseudonoise code sequence demodulation and phase demodulator
2 units operated in different delay time relationships to the
3 timing base of the reiterated modulation sequences. Pairs of
4 outputs of the units are connected to respective subtracter
5 circuits, each providing a signal representative of phase
6 differential of incident acoustic signals, or other forms of
7 signals, across virtual increments of the span established by a
8 pair of said delay time relationships.

9 n. Air-Backed Mandrel Modified Form of Invention

10 Figure 13 illustrates a so-called fiber-on-an-air-backed
11 mandrel assembly 801, useful in applications in which a fiber
12 optic span 9' is to be immersed in a liquid medium. Assembly
13 801 comprises a hollow cylindrical mandrel 803 having formed
14 therein a sealed central chamber 805 containing air or other
15 gaseous medium 807, which is compressible relative to the liquid
16 medium. A segment of span 9' of a ROSE system 2, FIG. 3, is
17 helically wound the cylindrical exterior surface of mandrel 803,
18 and suitably fixedly bonded to the surface. The cylindral wall
19 809 of mandrel 803 is of a material so chosen and of a thickness
20 so chosen to form a containic membrane with a hoop stiffness
21 that enables acoustic pressure wave signals incident upon
22 assembly 801 to be transformed into mandrel radial dimensional
23 variations. As a result of mandrel 801's geometry these radial
24 variations result in magnified longitudinal strain variations in

1 fiber 9'. It is to be appreciated that the physical structure
2 of assembly 801 inherently provides a spatial succession of two
3 locations along the fiber span, which a phase signal switch and
4 routing network 701 could select and route to become the virtual
5 bounding positions of a differential phase signal virtual
6 sensor. This is to say, positioning a mandrel wound span 9' as
7 a segment of a system total span 9 of ROSE system 2 can
8 facilitate providing a sequential pair of virtual sensor
9 locations along a span 9, and the provision of a corresponding
10 pair of delay circuits in correlator circuit 23 would cause
11 assembly 801 to operate as a differential phase signal sensor.

12 (4) ADVANTAGES AND NEW FEATURES

13 The invention enables the interrogation or time-delay
14 correlational multiplexing and demultiplexing of optical phase
15 signals.

16 The invention enables the interrogation of ROSE (Rayleigh
17 Optical Scattering and Encoding) fiber optic sensors. The
18 invention enables the spatial sorting and separation of the
19 temporal optical phases of backscattered optical signals arising
20 from a plurality (which upwardly may include a very large
21 number, for instance 5,000) of virtual optical sensors along
22 fibers or other optical mediums. The invention enables the
23 spatial decoding of backscattered optical signals with a
24 bandwidth of tens of kilohertz. The invention enables the

1 sensor locations along the fiber to be programmable. The
2 invention allows the electronic separation or segmentation of
3 the array of fiber sensors into programmable bounded lengths and
4 positions. Because the correlation signal, $c(t)$, can be
5 designed to be a continuous wave, the invention increases the
6 average optical power considerably over conventional pulsed
7 optical phase sensor interrogation methods. Because the
8 correlation signal $c(t)$ can be chosen to have spectrum spreading
9 properties for which dispreading electronic circuitry is readily
10 available, undesired optical fiber system noises, such as
11 reflection discontinuity noises due to cable couplings, can be
12 materially attenuated.

13 In hypothetically assessing the potential achievable by the
14 present invention with regard to employment of a common grade of
15 optical fiber cable buried beneath the ground surface as a
16 perimeter intrusion monitoring fiber span, the following
17 assumptions have been made: (i) signal to noise ratio (S/N)
18 degradation of Rayleigh effect light propagation in such an
19 optical fiber cable are assumed to be 0.5 db/km; (ii) it is
20 assumed there is a requirement for bandwidth of ten times that
21 of the geo-acoustic intruder signal needs to be detected; (iii)
22 and digital circuitry functions are performed employing
23 conventional "high end" clock rates. Using these assumptions,
24 and employing conventional single-mode or multimode fiber buried

1 6-12 inches underground, and using conventional engineering
2 methodology for noise effect prediction, it can be shown that
3 ROSE system 2 has the potential of sensing intruder caused geo-
4 acoustic, (i.e., seismic) signals along a length of fiber span
5 line as long as 8km or 5 miles. (This assessment is based upon
6 S/N degradations for flyback travel of signals from the
7 interrogation launch end of fiber span 9 to its remote end and
8 back.) The hypothetical segment resolution capability with such
9 a 8 km., or 5 mile line, would be 1 meter.

10 The invention provides a new capability of heterodyne
11 optical phase detection without resorting to dithered phase
12 carrier methods. The phase demodulation method introduces
13 heterodyne I & Q demodulation to produce cosine and sine phase
14 components, clipped signal amplitude stabilization techniques
15 and digital signal processing based phase detection. The
16 spatially differential phase detection method provided by the
17 invention enables the rejection of unwanted lead-in fiber phase
18 signals.

19 The details, materials step of operation and arrangement of
20 parts herein have been described and illustrated in order to
21 explain the nature of the invention. Many modifications in
22 these are possible by those skilled in the art within the
23 teachings herein of the invention. For example, while in system
24 2 the transformation from optical to r.f. signal takes place

1 prior to processing by programmable correlation 23, it is within
2 the skill of the art to design optical receiver 15 and
3 correlator system 23 to have the transformation take place
4 otherwise. Also, as an alternative to the previously described
5 mechanism for phase locking laser 3 and 45, the laser optical
6 wave on an optical path 39 can be passed through an acoustic-
7 optic modulator, sometimes called a Bragg Cell. The diffracted
8 optical wave exiting the acousto-optic modulator will be Doppler
9 shifted by an impinging-driving RF wave, that is translated into
10 a sound wave in the acousto-optic modulator, and the so-called
11 Bragg shifted-diffracted optical wave will exit the acousti-
12 optical modulator with an optical frequency equivalent to the
13 phase locked laser 45. The acousto-optically generated
14 lightwave, at an equivalent frequency of the phase locked laser
15 45, is sent along optical pathway 13 and becomes the local
16 oscillator input to heterodyne photoreceiver 15. An acousto-
17 optically frequency shifted version of the light in optical path
18 39 can therefore replace the phase locked light of coherent
19 optical source 45. Accordingly it is to be understood that
20 changes may be made by those skilled in the art within the
21 principle and scope of the inventions expressed in the appended
22 claims.

1 Attorney Docket No. 96518

2
3 NATURAL FIBER SPAN REFLECTOMETER PROVIDING A VIRTUAL PHASE
4 SIGNAL SENSING ARRAY CAPABILITY
5

6 ABSTRACT OF THE DISCLOSURE

7 A CW lightwave modulated by a continuously reiterated
8 pseudorandom code sequence is launched into an end of a span of
9 ordinary optical fiber cable. Portions of the launched
10 lightwave back propagate to the launch end from a continuum of
11 locations along the span because of innate fiber properties
12 including Rayleigh scattering. This is picked off the launch
13 end and heterodyned producing a r.f. beat signal. The r.f. beat
14 signal is processed by a plurality (which can be thousands) of
15 correlator type pseudonoise code sequence demodulation and phase
16 demodulator units, operated in different time delay
17 relationships to the timing base of the reiterated modulation
18 sequences. These units provide outputs representative of phase
19 variations in respective unique spectral components in the r.f.
20 beat signal caused by acoustic, or other forms of, signals
21 incident to virtual sensors at fiber positions corresponding to
22 the various time delay relationships.

POLARIZATION STATE VARIABLES

E: WAVE AMPLITUDE (VOLTS/METER)

θ : ROTATION ANGLE OF THE MAJOR AXIS

ψ : ELLIPTICITY ANGLE

ϕ : WAVE TEMPORAL PHASE

ω : WAVE RADIAN FREQUENCY

$\omega t + \phi$: INSTANTANEOUS ANGLE OF VECTOR

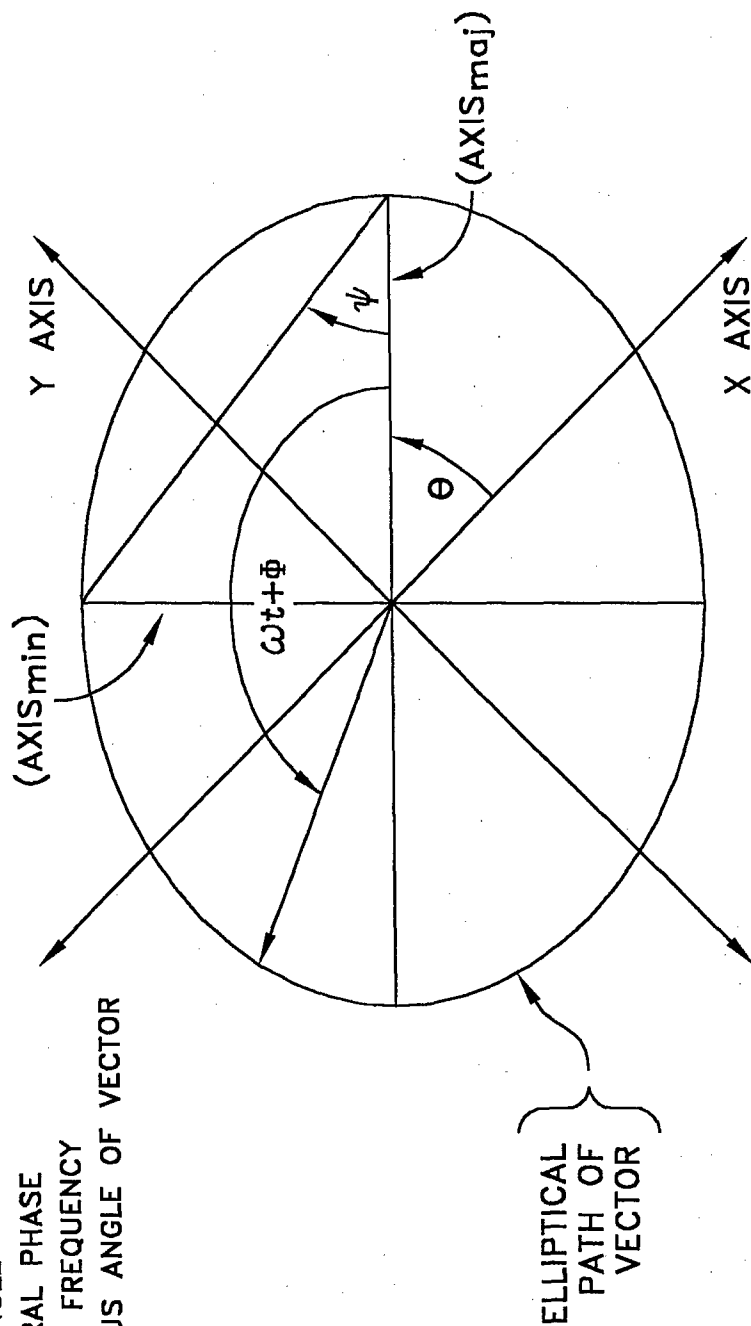


FIG. 1

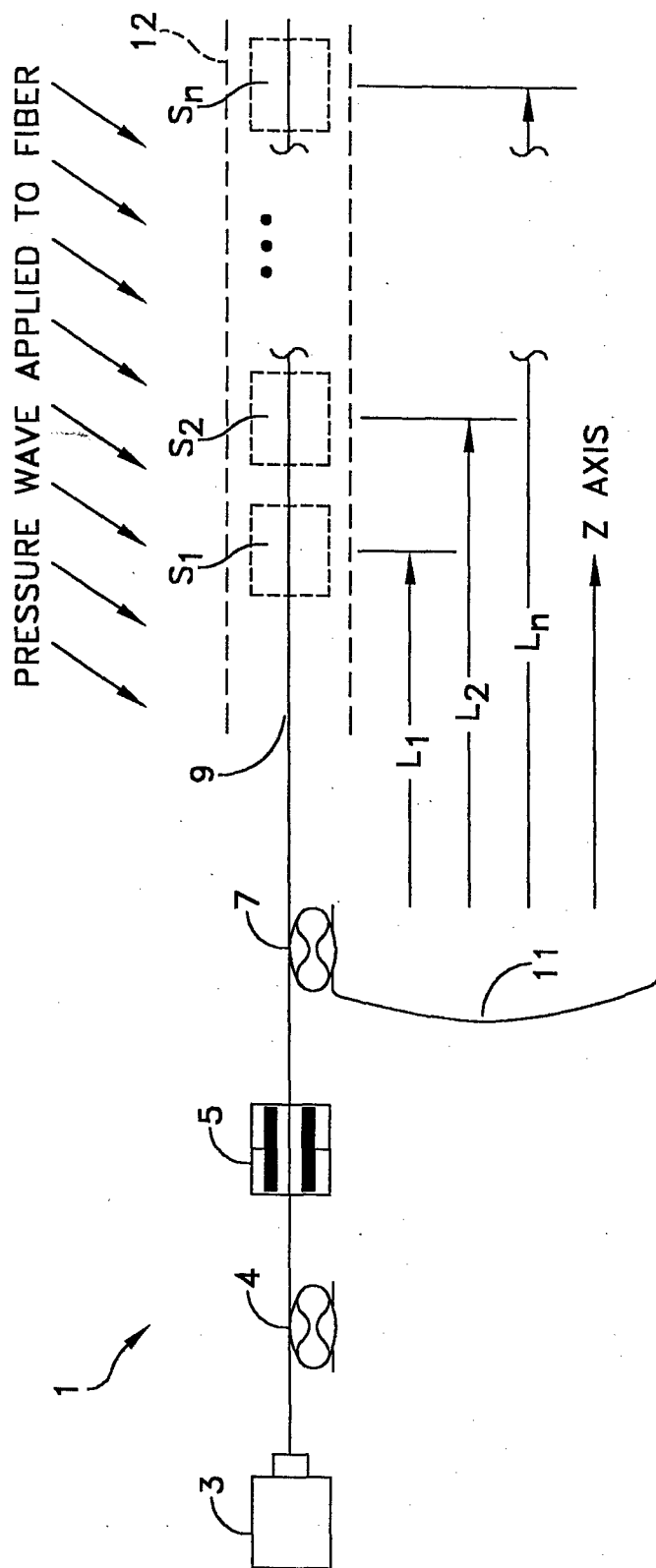


FIG. 2

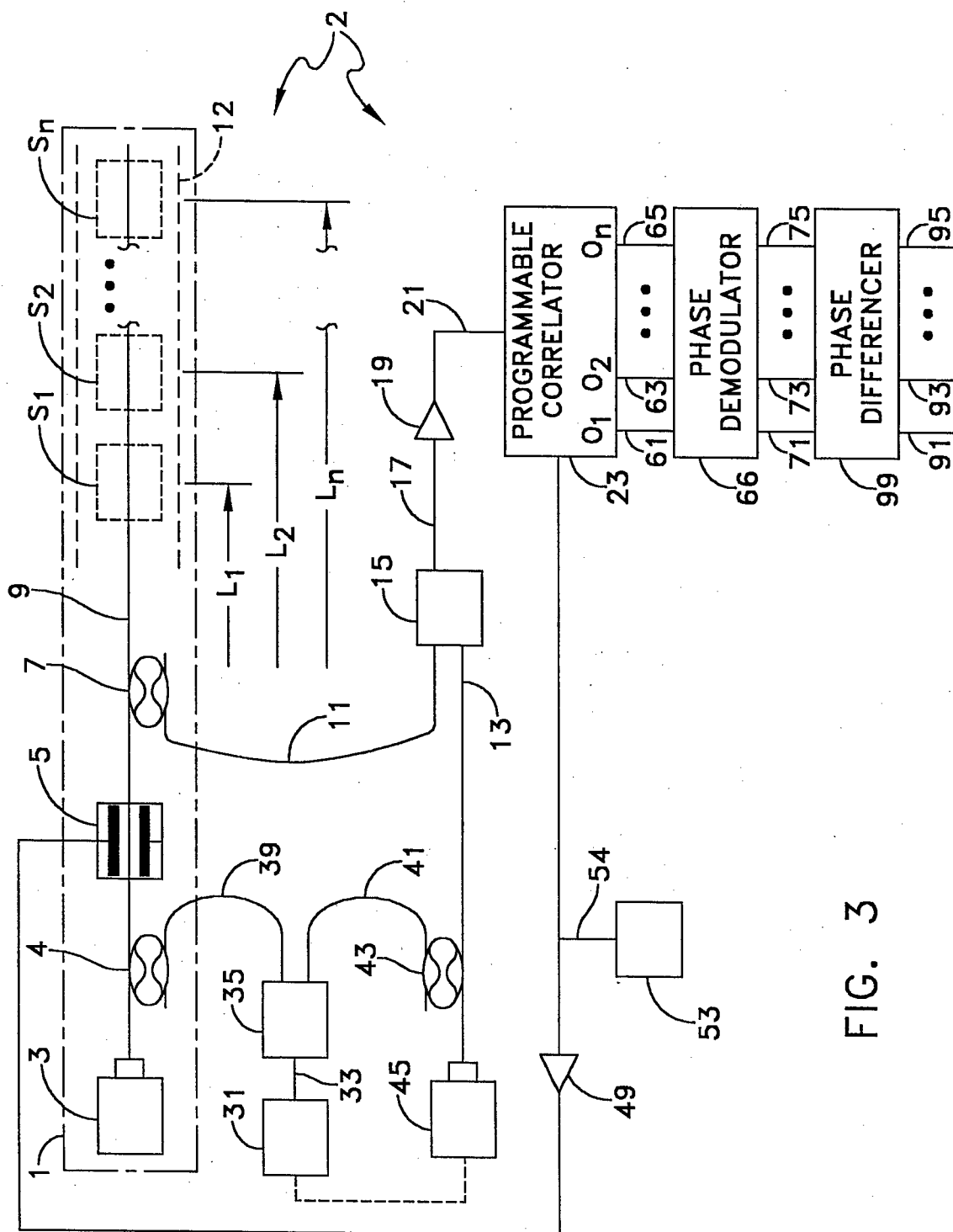


FIG. 3

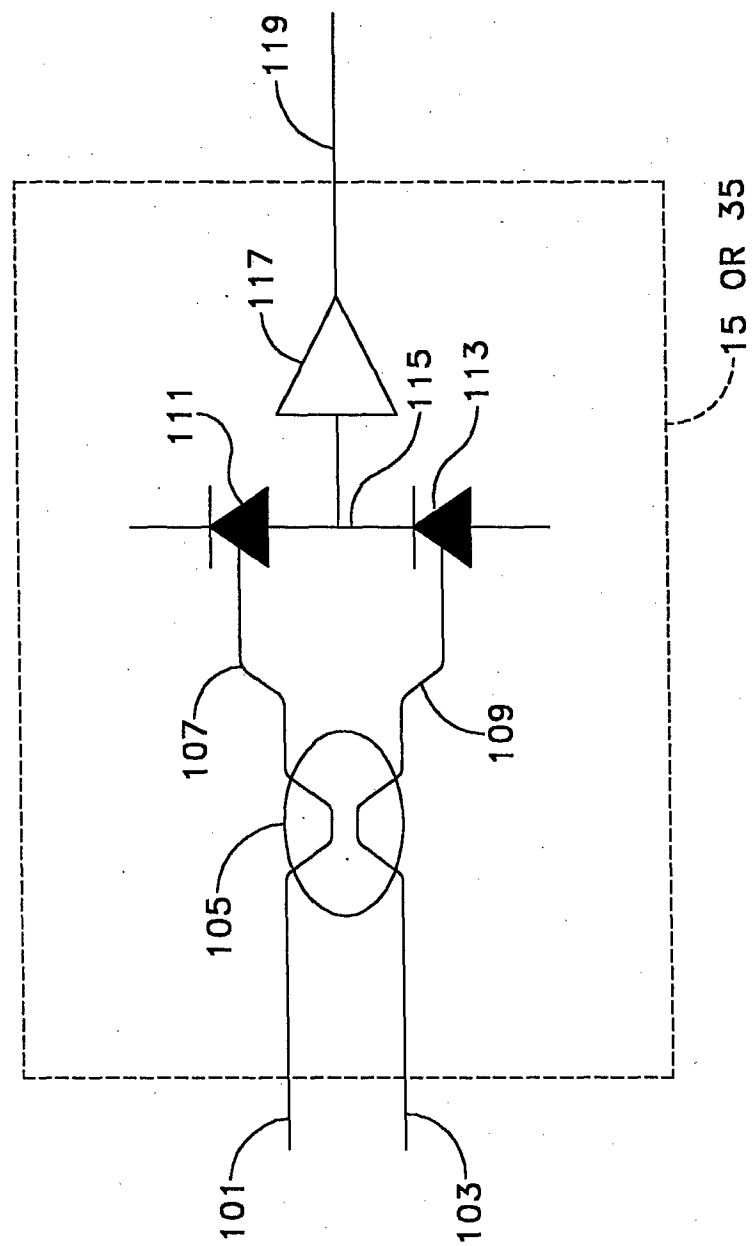


FIG. 4

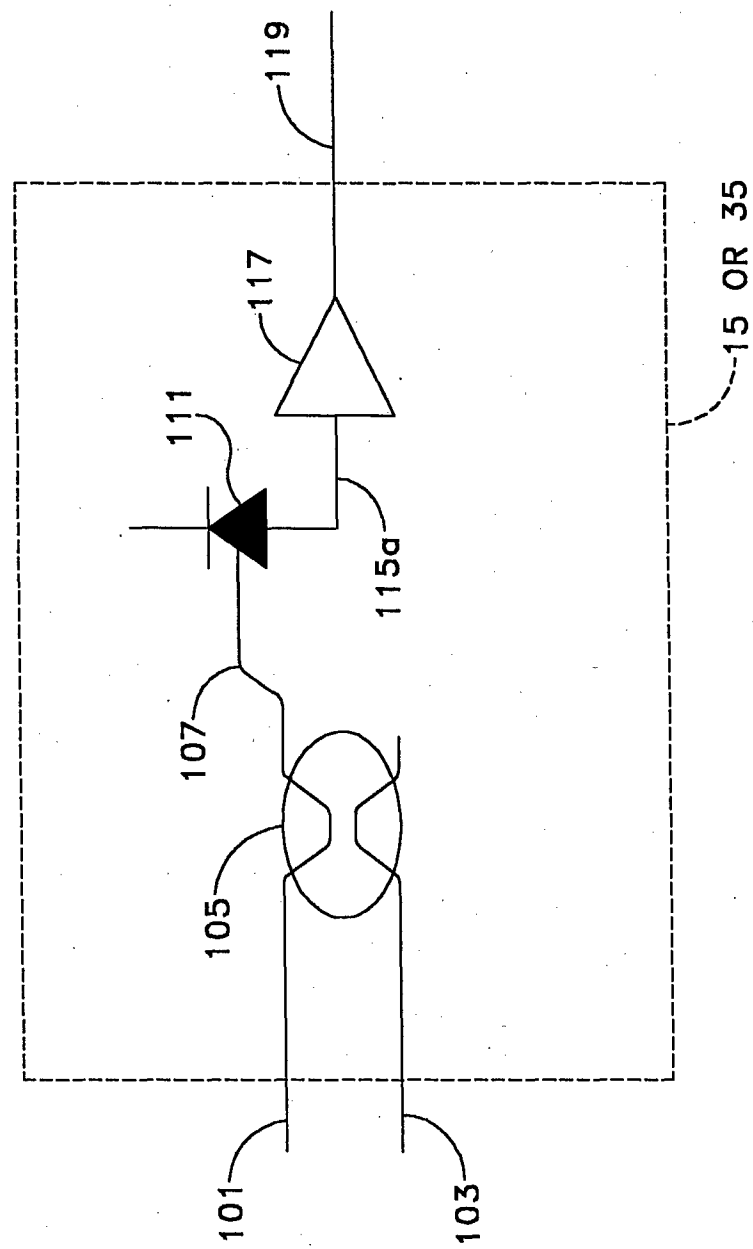


FIG. 5

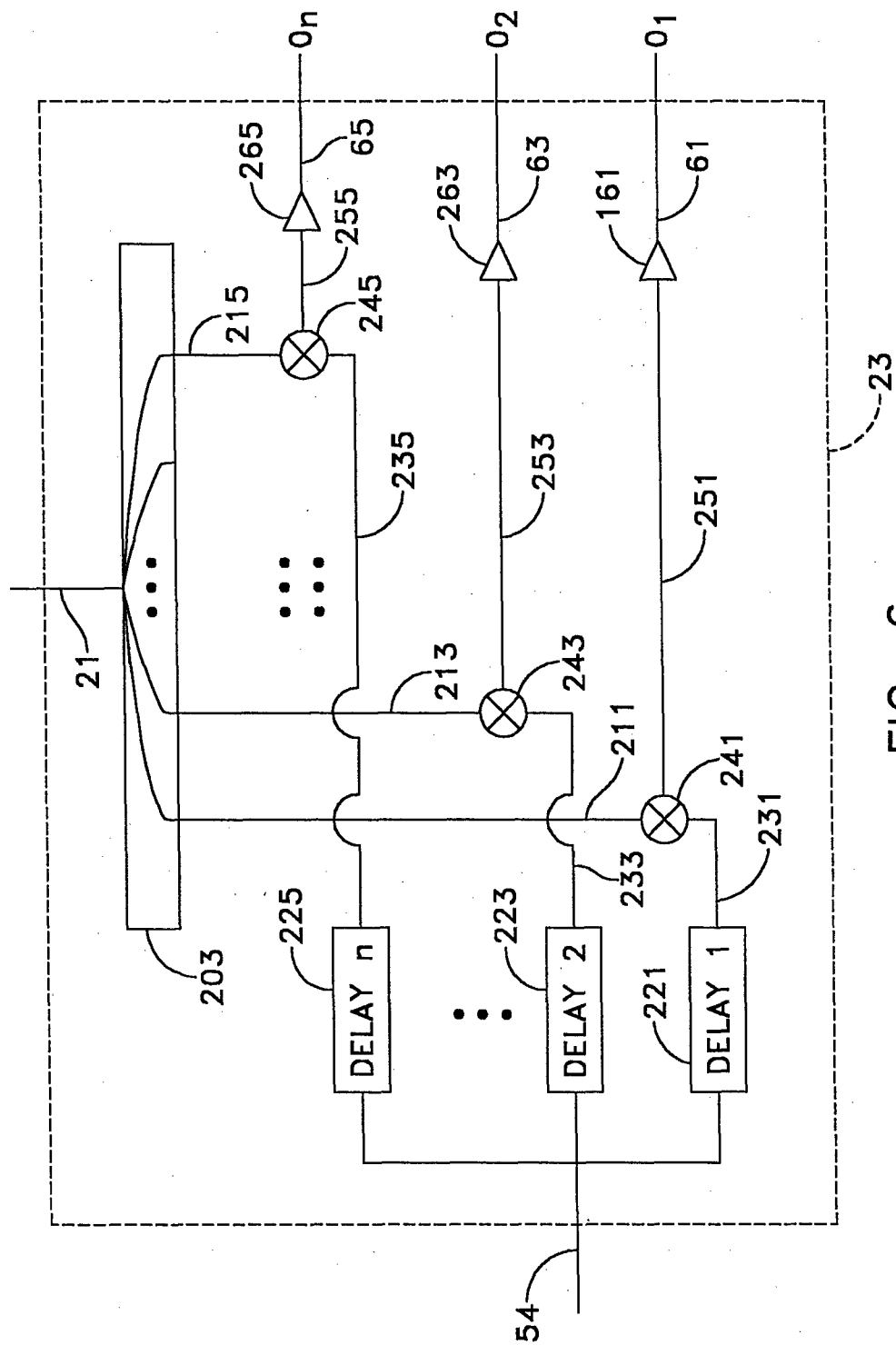


FIG. 6

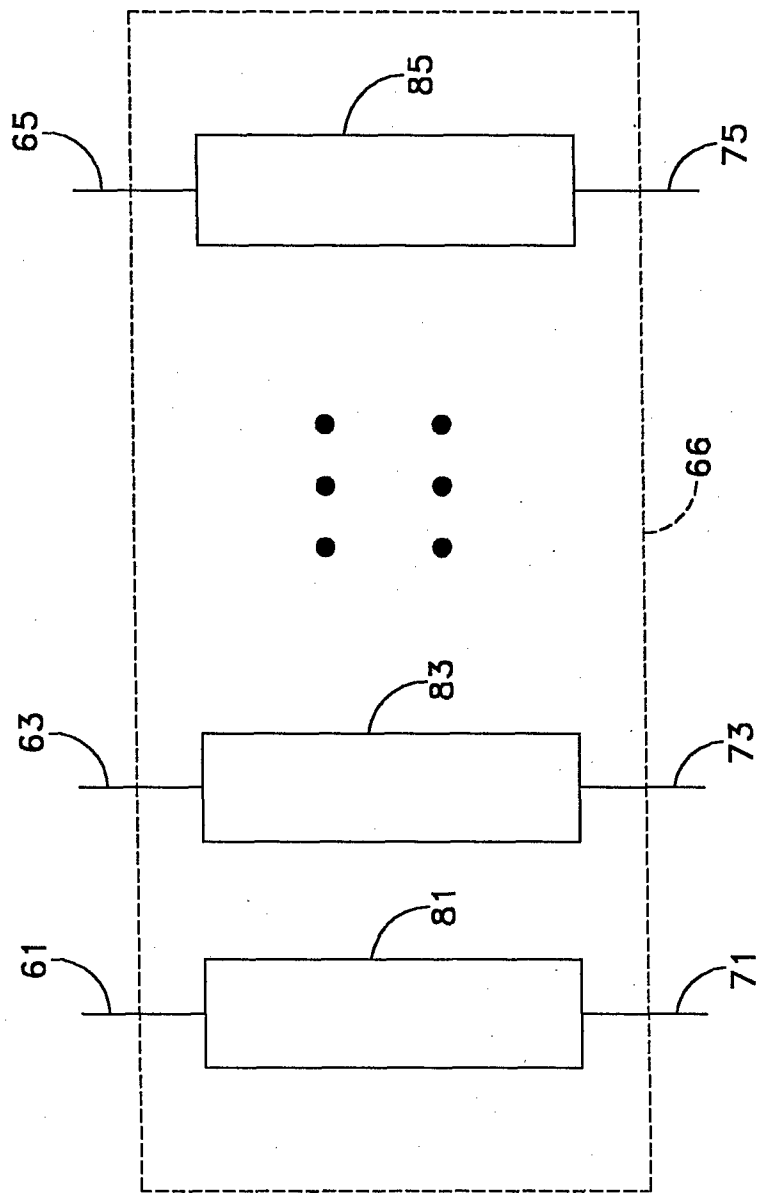


FIG. 7

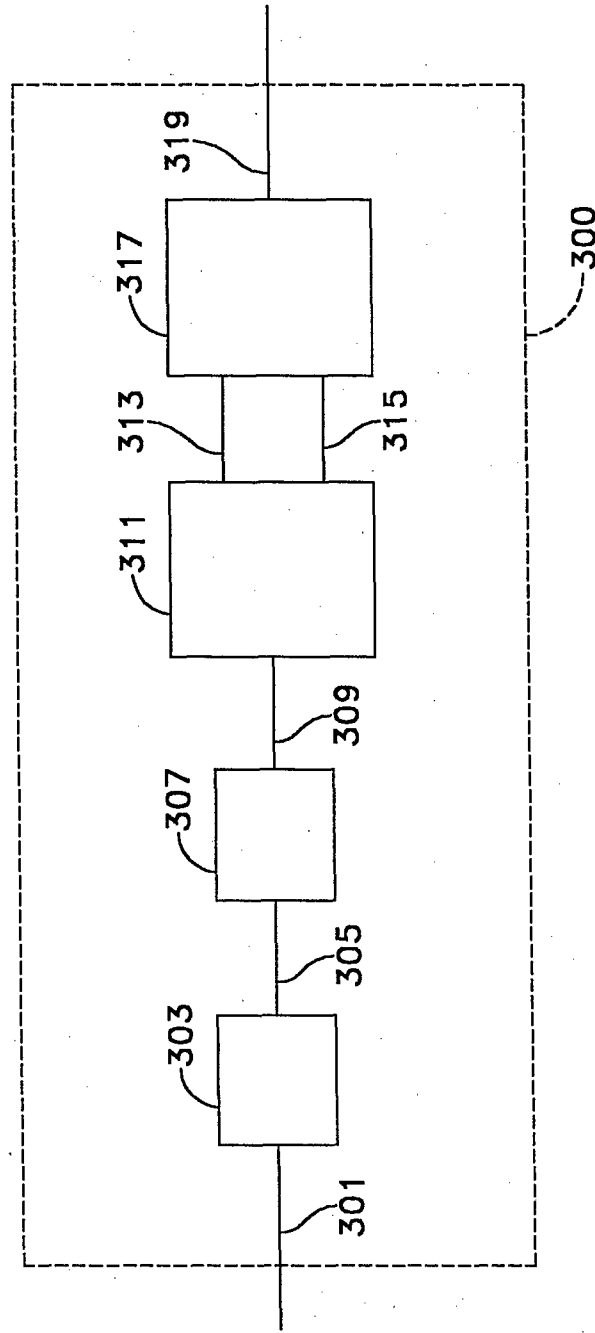


FIG. 8

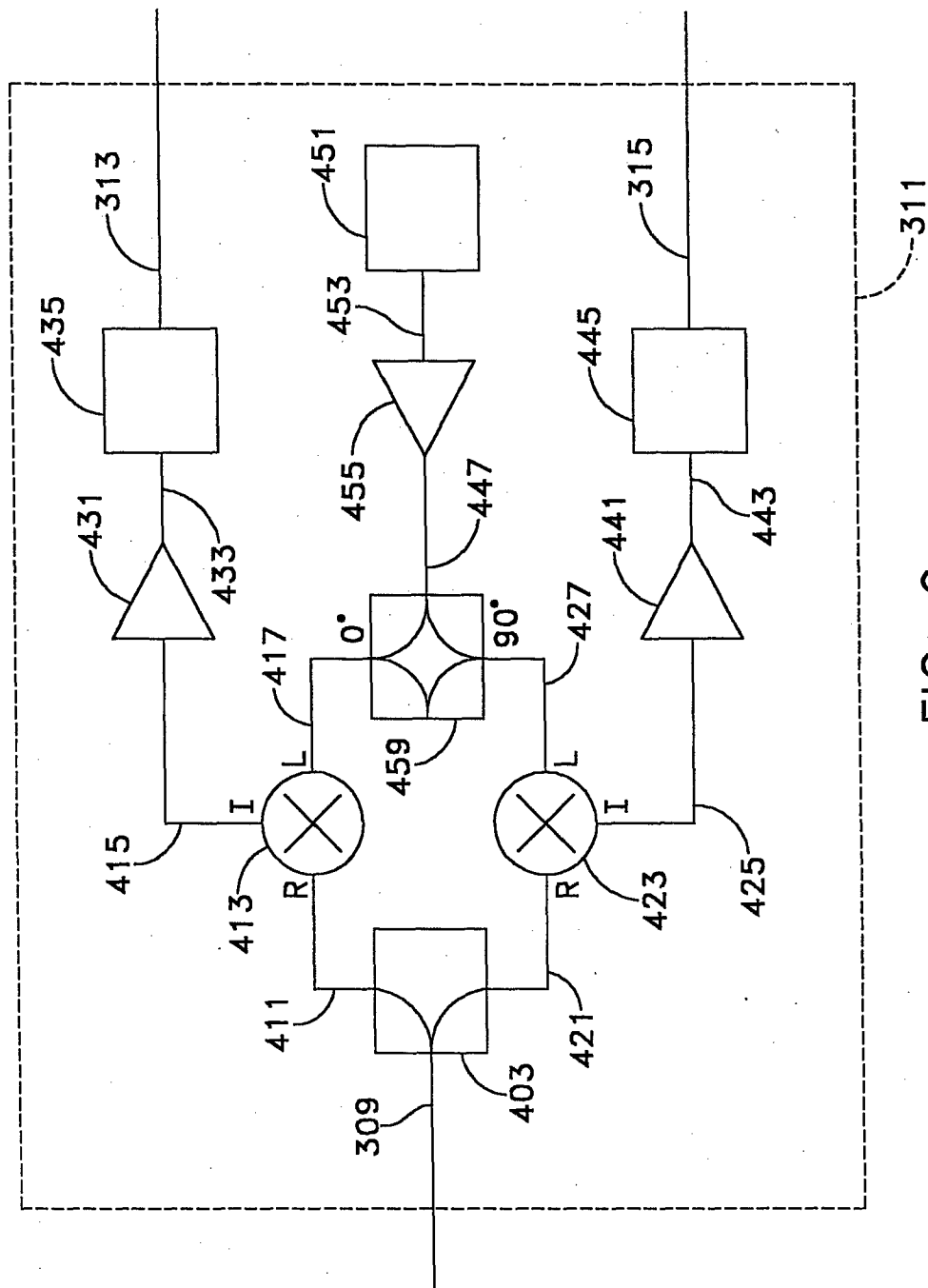


FIG. 9

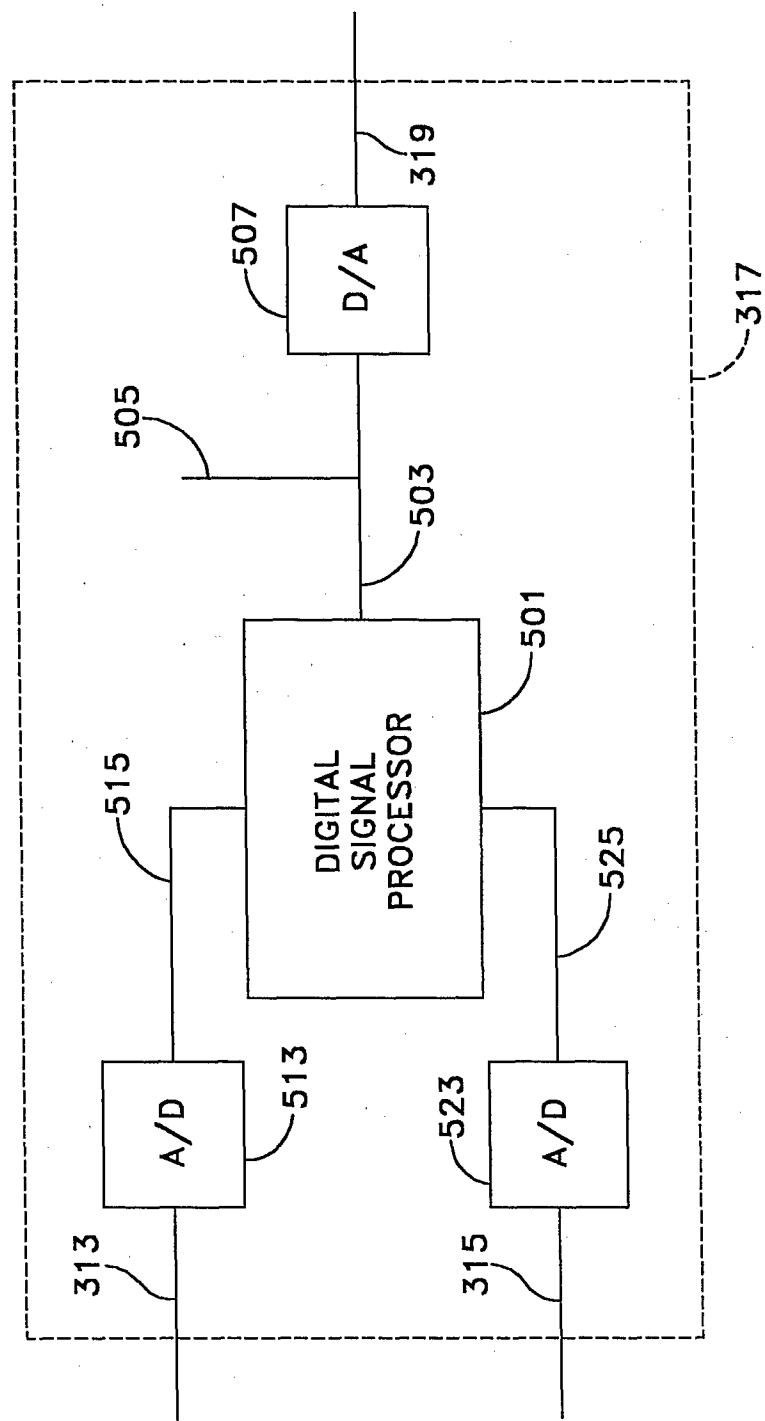


FIG. 10

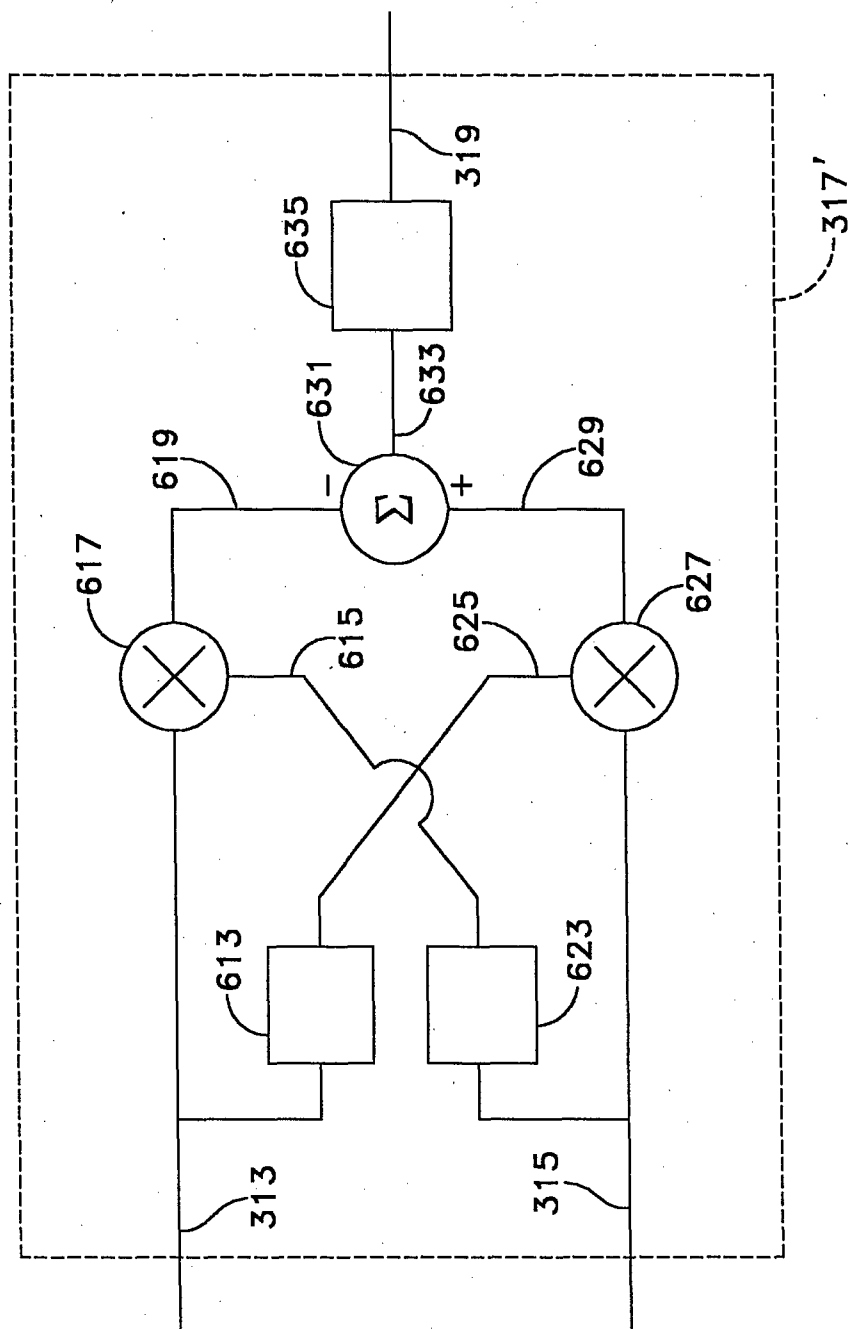


FIG. 11

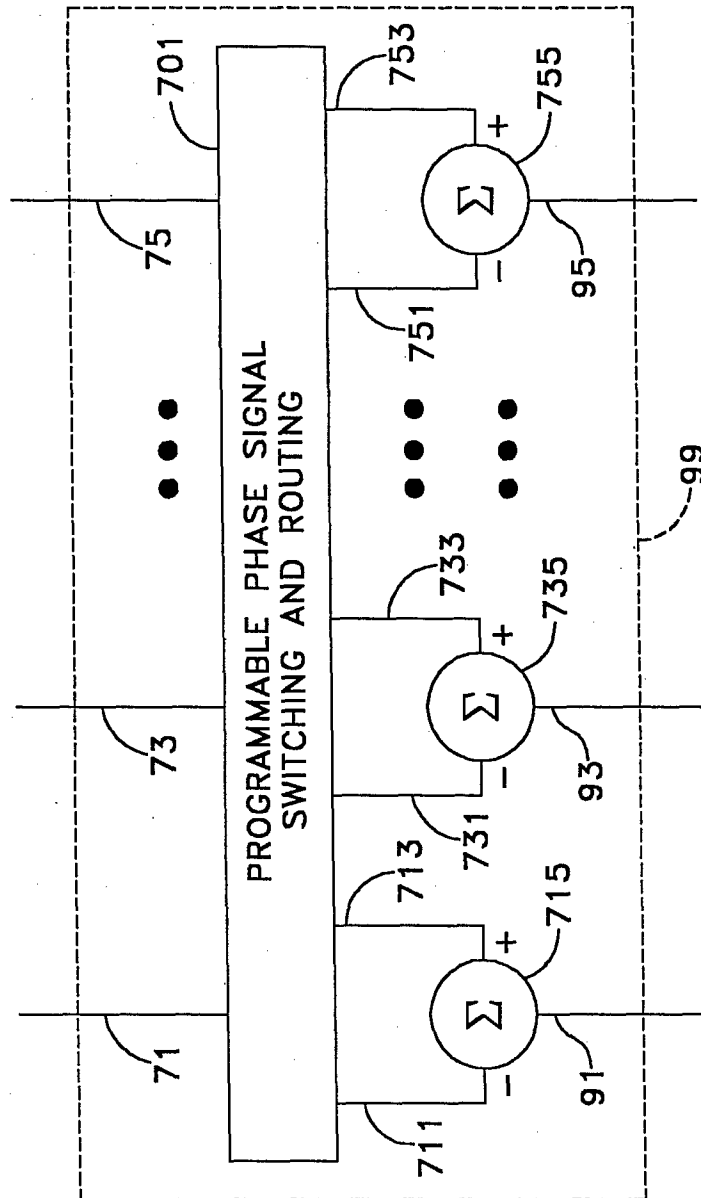


FIG. 12

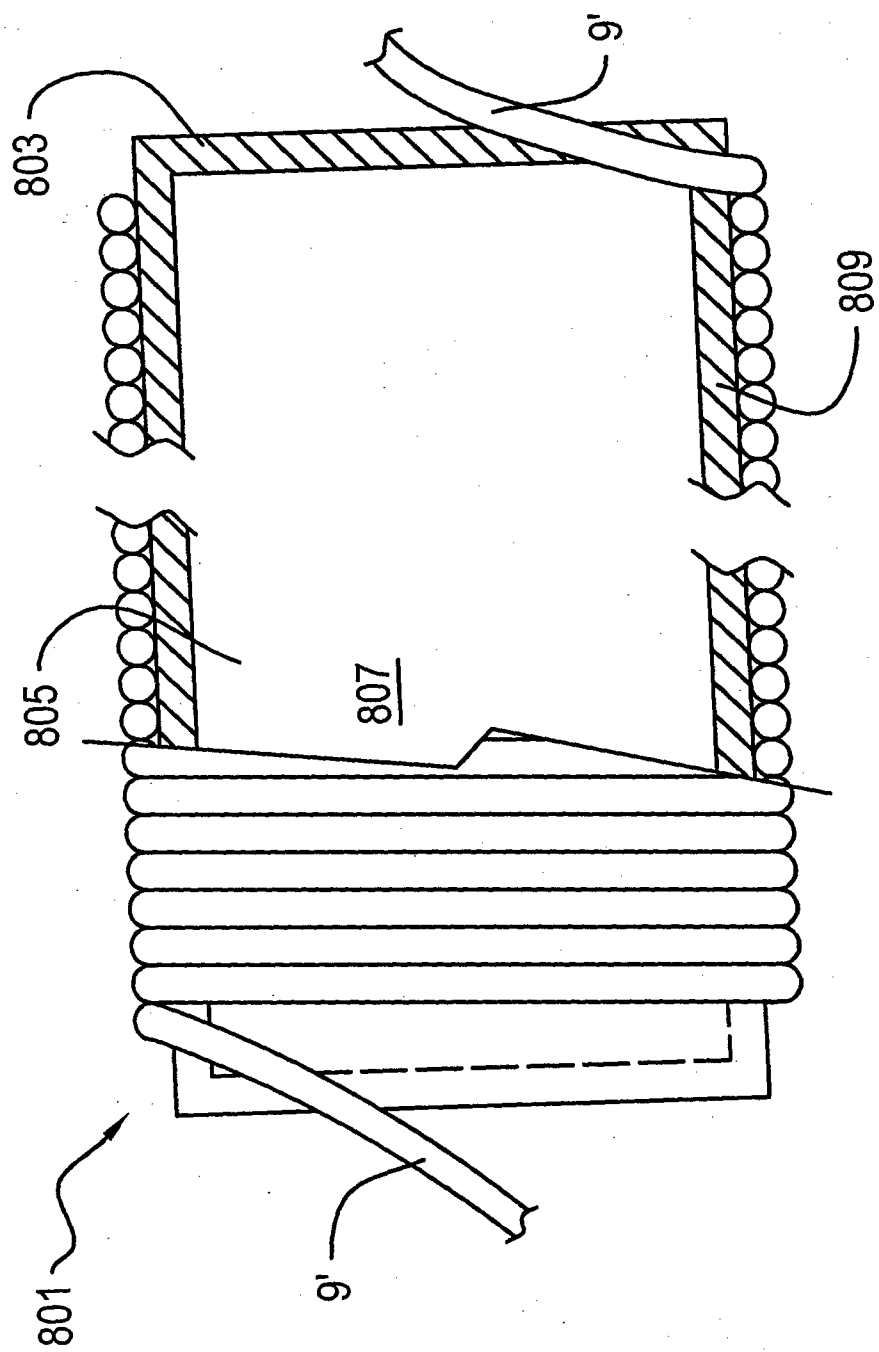


FIG. 13